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Identifying the effects of land use and policy on disturbance regimes in the Teanaway Community Forest, Washington

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IDENTIFYING THE EFFECTS OF LAND USE AND POLICY ON DISTURBANCE REGIMES IN THE TEANAWAY COMMUNITY FOREST, WASHINGTON

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ABSTRACT

The historic fire regime of the forests of the Eastern Cascades, Washington, has been described as one of high-frequency, low-severity fires using fire scar analysis. Over the past few centuries, the historically open, park-like ponderosa pine-dominated stands have been significantly altered due to Euro-American land use change such as fire exclusion, grazing, mining, and logging. The eventual encroachment of shade-tolerant species has resulted in a high-density forest structure that promotes rare, but extreme fire behavior and heightened susceptibility to insect attacks. As a result, the current disturbance regime is significantly less frequent and of higher severity, posing risks to forest resilience by changing its fundamental structure. The purpose of this study is to understand how land use change has altered the structure and composition of the Teanaway Community Forest (TCF). This research requires 1) remote sensing techniques to reconstruct the vegetation history and extent of the forest and to characterize the overall effects of land use change in the TCF and 2) the Forest Vegetation Simulator to predict future disturbance scenarios within individual stands in the TCF. Landsat imagery from years 1984, 2000, 2013, and 2017 were classified according to stand density and multispectral characteristics to assess changes in forest structure and composition. It was found that throughout the TCF, a continuous transition from more open ponderosa pine and mixed-conifer forest to uncharacteristically overstocked grand fir-dominated forest has occurred, which have drastically increased the potential for extreme fire behavior. These changes are due primarily to modern land use changes, including fire suppression, harvesting of large-diameter, fire resilient trees, grazing of fine fuels, and building of

roads, which have allowed the over-accumulation of hazardous fuels capable of supporting high-intensity wildfire. The FVS simulated that potential fire hazard will increase drastically over the next century due to increasing fuel loads and progression into later forest seral stages. When fire does occur in the TCF, high rates of tree mortality and economic repercussions can be expected. However, restoring the forest structure and composition to more closely emulate historic conditions will decrease wildfire severity potential and increase forest resilience to wildfire.

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CHAPTER I: INTRODUCTION

Research Problem

Prior to Euro-American settlement, the fire regimes of dry inland Pacific Northwest forests were primarily that of low-severity and high-frequency (Everett et al. 2000; Hessburg and Agee 2003; Wright and Agee 2004). Wildfire as frequent as every six to seven years, according to fire scar data in the eastern Cascades (Everett et al. 2000), maintained open, large-diameter ponderosa pine (*Pinus ponderosa)*-dominated stands that were resilient to wildfire, insect outbreaks, and other natural disturbances (Larson and Churchill 2012; Churchill et al. 2013; Hessburg et al. 2015)(Churchill et al. 2013; Larson and Churchill 2012; Hessburg et al. 2015). However, in the early nineteenth century, a policy of aggressive fire suppression was adopted due to significant public concerns after the 1910 Big Blowup, a series of wildfires that burned over 1.2 million hectares in Washington, Idaho, and Montana, and nearly one hundred firefighters (Williams 2005). In the century that followed, land use practices including grazing, logging, and mining, have degraded ponderosa pine forest health in the western United States (Haugo et al. 2010). The resulting forest structure is now characterized by small-diameter trees and dense stands (Fitzgerald 2005). Additionally, the absence of fire has shifted forest composition into predominantly shade-tolerant species and heavy fuel loads susceptible to high-severity fire and insect outbreaks (Fitzgerald 2005).

Numerous studies show that restoring historic fire regimes is the best way to improve eastern Cascade forest health and resiliency in fire-adapted forests (Everett et al. 2000; Wright and Agee 2004; S L Stephens et al. 2013). Thinning, mastication, and prescription burning are recommended to accomplish reduced fuel loads to varying levels of success in several studies carried out in Douglas-fir and ponderosa pine-dominated western U.S. forests (Agee and Skinner 2005; Youngblood et al. 2008; Fulé et al. 2012). Unfortunately, fire and other disturbances have increased in severity, far outside the historic regime, with the potential to devastate landscapes.

One area at risk of severe disturbance is the Teanaway Community Forest (TCF), located in central Washington. Over a century of fire exclusion, grazing, logging, and mining has greatly changed forest structure and composition over time (DNR 2015). The Department of Natural Resources and the Department of Fish and Wildlife have been collaboratively managing the TCF since 2013 with the intention of implementing a sustainable land management plan that includes protecting the watershed, water supply, recreational opportunities, and habitat, in addition to logging and grazing purposes (DNR 2015). Implementing effective fuel treatments is crucial in order to restore the forest structure and fire regime to pre-settlement conditions. However, particularly fire-prone of the forest first must be identified before they can be restored to historic levels of resilience that may otherwise withstand severe wildfire, such as the Jolly Mountain Fire of 2017 that burned nearly 15,000 hectares. This will allow the landscape to be used sustainably in the future in accordance with the Teanaway Community Forest Management Plan (DNR 2015).

Purpose

The purpose of this study was to use satellite imagery to determine how historic land use change has altered the composition of the TCF and to model forest health and future fire behavior with a goal of identifying and prioritizing forest stands that are in greatest need of restoration. Changes in land cover, including variables such as stand density, composition, and structure that have resulted from previous land use will help determine the most at-risk areas of the TCF. A fire history of the area was used as a reference for the historic fire regime and provide geographical boundaries of past fire occurrence (Wright and Agee 2004), while the Forest Vegetation Simulator with the Fire and Fuels Extension (FVS-FFE), a forest growth and yield model commonly used by the U.S. Forest Service, was used to model the future structural change of the TCF and its potential risk of disturbance. Based on this, the specific research questions for this study were: 1) How has land cover changed in the Teanaway River drainage since 1984; and 2) What forest cover types are most at risk of high-severity wildfire now and in the future as a result of land use change in the TCF?

The objectives of this study were:

1. To obtain stand inventories throughout the TCF to ensure an understanding of the current composition and structure of the Teanaway Community Forest.

Using fixed-circle plots 11.4-m radius and 30-m radius in size, individual tree and understory compositions were surveyed at 17 sites throughout the TCF to using a modified Federal Inventory Analysis (FIA) protocol. These observations were used as input data in the following objectives.

2. To create supervised classifications of various land cover types using Landsat imagery from years 1984, 2000, 2013, and 2017.

    Landsat imagery from years 1984, 2000, 2013, and 2017 were classified according multispectral characteristics to assess changes in forest composition and structure.

3. To model the potential fire hazard of various stands in the TCF using the Forest Vegetation Simulator with the Fire and Fuels Extension (FVS-FFE).

    The FVS was used to model stand structure, composition, and density of the stand at 10-year time intervals for one century using input data from Objective 1. These variables were summarized in a tree database file to be read by the simulator in order to determine which stands in the Teanaway river drainage have the potential for the most severe disturbance behavior in the next 100 years.

4. To combine fire hazard potential data with image classification maps to create a current fire risk map of the TCF.

    Fire hazard potential simulated by the FVS-FFE was mapped in Erdas Imagine to show what fire types could occur in the TCF in 2017 according to current stand composition and structure.

5. To provide land managers of the TCF management recommendations based on the results of this research.

   These results will provide managers with a map of current fire hazard potential in the TCF in addition to an estimation of future fire hazard potential in the next century if no fuel management practices are applied.

Significance

This research is significant for several reasons. First, quantifying how historic land use altered the landscape is crucial in understanding how disturbance regimes in the Teanaway have shifted away from historic regimes as a result of land use and policy change. Second, modeling potential wildfire behavior will help clarify where restoration methods, such as thinning and prescription burning to reduce fuel continuity, will be most effective within the TCF (Reinhardt and Crookston 2003). These disturbance-prone areas can then be prioritized by land managers for restoration. Third, any native vegetation and wildlife is at risk for diminished vitality, as they have likely co-evolved along with the natural disturbance regimes, and may be suffering as these regimes undergo rapid change (Hessburg et al. 2012), which may increase the severity of damage to the forest. Fourth, the TCF was purchased by the state as a part of a larger watershed restoration plan. Future management goals of the TCF include incorporating recreational use into the forest while maintaining historic activities such as grazing and timber harvest (DNR 2015). Therefore, understanding how land use alters disturbance regimes is critical in order to manage the TCF sustainably. The results of this study will help determine how the effects of land use change have physically manifested in the landscape as well as future implications for restoration.

CHAPTER II: LITERATURE REVIEW

Forests of the eastern Cascades have undergone extensive alteration as a result of land use and policy change, which has resulted in significant ecosystem degradation (Fitzgerald 2005). A fire scar-based history of the Teanaway River drainage shows frequent fire activity up until fire exclusion became prevalent after approximately 1900, after which time the size and extent of recorded fires reduced dramatically (Wright and Agee 2004). The modern disturbance regime is much more severe and the forests lack resilience. However, fuel treatments, when applied correctly, can help restore historic spatial heterogeneity to the landscape to alleviate fire severity and promotes resilience to disturbance (Fitzgerald 2005).

Historic Disturbance Regimes of Eastern Cascade Forests

Several factors have helped determine the historic disturbance regimes of the eastern Cascades prior to Euro-American settlement, which can be examined at both local and landscape scales (Agee 1996). The arrangement and continuity of fuels in a stand, both vertically and horizontally, defines how intense the fire is, or how much energy is released. This includes surface fuels, ladder fuels, size (and therefore resistance to fire mortality) of the trees, vegetation composition, stand density, fuel moisture, and other variables. At larger scales, the spatial heterogeneity of the stand determines how fire moves across the landscape, and ultimately, the overall disturbance regime (Agee 1996).

Prior to Euro-American settlement, eastern Cascade forests were generally of open and patchy structure, uneven-aged, and dominated by shade-intolerant ponderosa pine trees with some Douglas-fir (*Pseudotsuga menziesii*) and grand fir (*Abies grandis*) (Hessburg and Agee 2003; Fitzgerald 2005). Ponderosa pine trees in particular are well adapted to frequent fire with characteristics such as thick bark, deep roots, and high crowns that reduce the likelihood of wildfire mortality (Fitzgerald 2005). A sparse understory carried surface fires with short flame lengths that consumed shrubs and seedlings, keeping the ground relatively clear of fuels and new growth, while lower stand density discouraged running crown fires (Fitzgerald 2005). Surface fires occurred often in the Teanaway River valley, the most common interval of which was every 8 years across all sites (Wright and Agee 2004). Late summer lightning strikes in the absence of precipitation were, and continue to be, a common source of ignition throughout the inland Pacific Northwest (Rorig and Ferguson 2002). Evidence exists that Native Americans also promoted the frequent fire regime by regularly burning areas of the Pacific Northwest landscape to prevent the encroachment of the forest into clearings and to stimulate the growth of edible plants, such as huckleberries and camas (Boyd 1999, Hessburg and Agee 2003, Walsh, Duke, and Haydon 2018). Historic oral accounts of Spokan elders, originating from the Colombia Plateau in southeastern Washington, reveal that frequent burning also created ideal foraging conditions that increased game availability. The resulting advantages, including low fuel accumulation and tree mortality rates, are simply a product of Native American landscape manipulation to maintain traditional food sources, reflecting a good understanding of the ecological processes involved (Boyd 1999, Stine et al., 2014). The low-severity disturbance regime supported the open forest structure, and vice versa.

The historic fire regimes of the lower Teanaway Valley are known from a study by Wright and Agee (2004) in which they observed the frequency and extent of fire scars using extensive fieldwork and dendrochronological methods. The study area encompassed 30,000 ha of forest and 92 field sites were included. Their results show that prior to Euro-American settlement, fire was a frequent occurrence in the Teanaway River drainage, and most fires occurred late in the summer or fall as a result of drier fuels and possibly intentional human ignition as often as every three years. At the end of the 19th century, fire frequency and size significantly reduced, likely due to the coupled effects of suppression efforts and a cooling climate (Wright and Agee 2004). Much of the fire activity represented by the fire scar data is low- to medium-severity fire behavior. Too mild a fire would not scar a tree, while too extreme a fire would result in tree mortality, therefore leaving no evidence. Unfortunately, it is unclear whether there are very low- or high-severity fires not represented in the fire history record. Additionally, mixed-severity fires could leave an incomplete record in terms of fire extent. Clarity on the extent of each fire is further compromised due to assumptions about breaks in fuel, such as rivers (Wright and Agee 2004).

The modern and historic characteristics of forests can also be determined using air photos. In a study by Hessburg and Smith (1999) to determine forest structure change in the interior Colombia Basin, historic air photos dating back to 1938 were used to create vegetation reconstructions to compare to modern aerial imagery. Land cover classes were delineated based on subjective analysis of visual attributes, such as composition and structure, and some digital attributes, such as topography. The classes were then assigned a disturbance vulnerability rating using a combination of methods from existing literature and expert opinion. It was found that the both the past and present composition, structure, and disturbance regime of each patch type was crucial in determining reference variation departures and that modern conditions were outside the historical range of variability in many stands. This allowed the researchers to make inferences about how and why modern forest structure has changed over time and how to restore the forest to historic conditions.

Historic Land Use and Policy of the Eastern Cascades

Alterations to natural disturbance regimes in the eastern Cascades are suggested to be a result of land use change introduced by Euro-Americans in the late 1800s. With the massive reduction in population and subsequent isolation of Native Americans to reservations, traditional frequent burning halted (Hessburg and Agee 2003; Walsh, Duke, and Haydon 2018). Significant population growth expanded westward during this time and settlers brought with them livestock animals, such as cattle, sheep, and horses. As a result, widespread grazing began on what is now public land in the western U.S. in the 1860s (Hessburg and Agee 2003). As many as 15,000 sheep were reported to have been grazing in the Teanaway in the early 1900s (Plummer 1902). Heavy grazing promoted early fire exclusion by reducing fine fuels that carried surface fires, reducing the likelihood that naturally-ignited fires would burn expansive areas. This allowed for the accumulation of surface and ladder fuels with simultaneous increases in stand density, which significantly increased the potential for extreme fire behavior (Churchill et al. 2013; Hessburg et al. 2015). Grazing permits were not required until 1906, but grazing did not significantly decrease until the approval of the Taylor Grazing Act of 1934. The Act enforced certain regulations to slow the previously unrestricted overgrazing of the West originally meant to encourage westward settlement and bolstered by a general misunderstanding of rangeland management (BLM 2019).

The construction of mining roads and railroads beginning in the 1850s further fragmented eastern Cascade forests, reducing fuel continuity capable of carrying surface fires (Hessburg and Agee 2003). Both ponderosa pines and tamarack (*Larix laricina*) were often selectively harvested to satisfy demand for both development and railroad infrastructure (Henderson 1990; Hessburg and Agee 2003). As a response to the shortage of high quality lumber in the eastern United States, an abundance of lumber was transported across the United States in the early twentieth century using the newly completed transcontinental railroad.

Old growth ponderosa pine trees were highly sought after because of both their quality and size and were mostly removed from the eastern Cascades by the 1960s, after which time other species were targeted for harvest (Hessburg and Agee 2003). The development of technologies, such as chainsaws and tractors, followed by professional forestry techniques such as clearcutting and plantation forestry, from approximately 1950 to the 1980s, maximized yield by large lumber companies. Removal of large fire-resistant trees such as ponderosa pine opened up the landscape to younger, less resilient trees and thicker understories capable of fueling extreme fire behavior and decreasing the likelihood of stand survival after severe wildfires (Fitzgerald 2005; Churchill et al. 2013; Hessburg et al. 2016).

The change in disturbance regimes is reflected in the fire history record. At approximately 1900, fire size and frequency dramatically decreased in the TCF (Wright and Agee 2004). Limiting environmental factors excluded certain areas from frequent fire, creating ‘islands’ of older-aged trees called fire refugia (Camp et al. 1997). Currently, fire suppression has allowed these islands to form and connect in areas with and without these limiting factors, increasing fuel accumulation in disturbance susceptible environments (Camp et al. 1997). Fire severity increased as a result of higher fuel loads, but frequency and extent is much lower (Wright and Agee, 2004). This fire regime is a positive feedback, as stand-replacing fires promote even-aged growth forests which are highly susceptible to insect, disease, and future extreme fire behavior (Camp 1999).

Recent policy changes were designed to reverse the detrimental effects of past land use due at least in part to the environmental movement in the 1960s (Hessburg and Agee 2003). Legislation was passed to improve wilderness management, including redefining fire as a crucial process in many ecosystems. By doing so, the Forest Service transitioned somewhat away from a fire suppression to a fire management perspective that is in place today by allowing some fires to run their course, especially in national forests (Williams 2005). Other land management policies have since been enacted to increase forest health. The National Environmental Policy Act of 1970 requires federal agencies to create an interdisciplinary report detailing any potential environmental impacts before the implementation of any project. The Endangered Species Act of 1973 applied protections to species and their habitats deemed threatened by U.S. Fish and Wildlife, which often requires the conservation of forest land. The Federal Land Policy and Management Act of 1976, or the Organic Act, allowed the federal government to delineate portions of land to be managed by the National Park Service, essentially allowing certain places to be preserved from potentially damaging land use practices (BLM 2001).

Synergistic Disturbances of Eastern Cascade Forests

In addition to extreme fire behavior, insect outbreaks are a common form of disturbance in the forests of the western U.S., the severity of which is intensified by the effects of fire exclusion (Lillybridge et al. 1995; Stine et al. 2014). High forest density and homogeneous stand structure caused by lack of fire allows insects to spread with ease, furthering the extent and resulting damage (Stine et al. 2014). Weakened trees, made so by drought and other stresses, are more susceptible to insect-caused mortality. Flaking ponderosa pine bark contributes to surface fuels in the immediate vicinity of the trees, increasing the potential damage to both the cambial layer and roots, resulting in a much higher risk of mortality and to insect damage afterward (Fitzgerald 2005). In addition, cold temperatures are a common cause of beetle mortality, while higher temperatures and longer warm seasons increase beetle vigorousness, leading to higher populations and more resultant damage (Bentz et al. 2010). The life cycles of these beetle species vary anywhere from several life cycles in one season to a single life cycle taking up to several years, largely dependent upon temperature and duration of the warm season (Stine et al. 2014).

In the inland Pacific Northwest, Douglas-fir and grand fir are most susceptible to the fir engraver (*Scolytus ventralis*), the Douglas-fir tussock moth (*Orgyia pseudotsugata*), and the Douglas-fir beetle (*Dendroctonus pseudotsugae*). Ponderosa pine and lodgepole pine (*Pinus contorta*) are commonly affected by western pine beetle (*Dendroctonus brevicomis*), mountain pine beetle (*Dendroctonus ponderosae*), and the pine engraver (*Ips pini*) (Lillybridge et al. 1995; Stine et al. 2014). Most of these species have the ability to cause mortality at the landscape level (Stine et al. 2014).

Dwarf mistletoe (*Arceuthobium spp.*), a disease that spreads throughout tree crowns by spreading spores to nearby trees, contributes to structural complexity, greatly increasing torching potential and vulnerability to insect attack. More than 26 percent of ponderosa pine and 43 percent of Douglas-firs are likely affected throughout the Kittitas County area in central Washington, and is also common in other species including grand fir, lodgepole pine, and western larch (*Larix occidentalis*) (Lillybridge et al. 1995; USDA 2010). The spread and subsequent damage caused by mistletoe and other pathogens tends to be exacerbated by high density, homogeneous forest structure (Stine et al. 2014).

It would be ill advised to attempt complete eradication of insects and pathogens from forests, however. Snags and felled trees killed by insects or disease provide food and habitat for fauna and promote structural variability, and the insects themselves interact with various organisms important to forest health. It is recommended to reduce the severity and frequency of insect attacks to a tolerable level by using various management techniques, such as thinning and increasing spatial heterogeneity (Stine et al. 2014; Hood, Baker, and Sala 2016). Doing so reduces the chance of spread of both insects and pathogens, usually restricting mortality to dense patches of trees (Fettig et al. 2007).

Drought is a natural disturbance that is becoming more intense and frequent with climate change, which has caused a rise in tree mortality in mixed-conifer forests largely due to multiple and lengthening warm seasons (Taylor and Guarı 2005). Species such as ponderosa pine tend to be both drought- and fire-tolerant, but hotter temperatures coupled with a forest composition shift and increasing tree density are reducing moisture availability beyond ponderosa pine thresholds, resulting in higher mortalities (Jerry F. Franklin, Hagmann, and Urgenson 2014; A. L. Westerling, H. G. Hidalgo, D. R. Cayan 2019). Additionally, moisture competition caused by drought stress in the eastern Cascades amplifies vulnerability to other disturbances, including insects, pathogens, and fire, exacerbating potential damage from these events (Mattson and Haack 1987; Stine et al. 2014). This is especially true for drought-intolerant species, such as grand fir, that are becoming more dominant in many fire-excluded dry forests (Stine et al. 2014).

Forest Restoration

To combat the effects of fire exclusion, researchers have agreed that the restoration of dry forests to their historic, fire-frequent condition is the best way to increase forest resilience (Churchill et al. 2013; Stine et al. 2014; Hood, Baker, and Sala

2016). Rehabilitation of western U.S. forests in the form of fuel reduction has been studied widely (Youngblood et al. 2008; Fulé et al. 2012; Larson and Churchill 2012; Scott L. Stephens et al. 2012). Methods including mechanical thinning, mastication, and prescription burning have been experimented with on a variety of spatial and temporal scales in the region (Agee 1996; Agee and Skinner 2005; Hood, Baker, and Sala 2016). Mechanical thinning refers to the manual removal of trees, branches, and surface fuels, while mastication is the process of grinding up large fuels using machinery (Wimberly and Liu 2014). These methods can be followed up with small-scale prescription burning to remove fine fuels as an effective combination (Arkle, Pilliod, and Welty 2012; Fulé et al. 2012). In a study of forest resilience, the combination of prescribed burning and thinning reduced the potential severity of extreme wildfire behavior, thereby reducing mountain pine beetle spread and subsequent damage in a mixed-conifer forest in Montana due to reduced stand density and composition shift (Hood, Baker, and Sala 2016).

The goals of fuel treatments are not only to reduce the quantity of fuel available to burn when a fire does occur, thus reducing the resulting intensity while conserving large fire-resistant trees (Agee and Skinner 2005), but also to restore spatial heterogeneity in such a way that damage from fire, insects, or pathogens is confined to patches and is unable to spread through entire landscapes (Churchill et al. 2013). One way to achieve this was done by creating an algorithm of spaces, patches and individual trees to be used as guidelines for creating effective spatial heterogeneity. Implementing this algorithm into restoration practices achieved spatial heterogeneity comparable to historic reference conditions, reducing overall susceptibility to severe disturbance, such as insect spread and fire (Churchill et al. 2013).

The success of fuel treatments are dependent on the both spatial extent and frequency of application (Scott L. Stephens et al. 2012). Much like a natural disturbance regime, fuel treatments should be applied regularly to maintain open forest structure, enabling fire to return to the landscape naturally (Agee and Skinner 2005). Fuel treatments must be applied consistently under these circumstances to discourage fuel accumulation. These methods have shown various degrees of success (Harrod, McRae, and Hartl 1999; Agee and Skinner 2005). Under ideal conditions, fuel treatments would reduce the potential for high-severity fires and allow surface fires to reenter the landscape naturally. For example, a study done in the Douglas-fir and ponderosa pine-dominated Payette National Forest, Idaho, showed that wildfires, within three years after various prescribed burn treatments were applied, were significantly less severe than those in the surrounding areas (Arkle, Pilliod, and Welty 2012). Another study done in a ponderosa pine-dominated forest of northern California used thinning treatments to reduce the likelihood of severe wildfires spreading into the extensive wildland-urban interface. Overall, a combination of prescribed burning and thinning was found to be the most effective to mitigate severe fire risk and promote mild and frequent surface fires (Symons, Fairbanks, and Skinner 2008).

Risks associated with prescribed burns include escaped fires and significant smoke inhalation which are increasingly dangerous when coupled with climate change and development in the wildland-urban interface (Wimberly and Liu 2014). For these reasons, mechanical thinning is often the preferred and most acceptable method of fuel treatments, although this tends to be much more labor intensive, economically challenging, and difficult or impossible to utilize in topographically complex areas (Scott L. Stephens et al. 2012).

Reconstructing Historic Land Cover Change using Remote Sensing Methods

To better understand how the landscape has changed fundamentally through time resulting from human influence, aerial and satellite imagery can be used to determine changes in forest structure and composition (Callister et al. 2016). Historic air photos of varying resolutions, both color and grayscale, were taken in many areas in the early- to mid-twentieth century. Although air photo interpretation cannot be compared to *in situ* data, overall landscape structure and broad land cover types can be observed and compared to later images. Some historic air photo studies quantify parameters such as textural heterogeneity that as important for identifying vegetation cover types and associated disturbance regimes (Morgan and Gergel 2010), but high levels of distortion reduce reliability. More often, air photos are described qualitatively in terms of tone, texture, pattern, shadow, shape, and context, and compared to modern images (Morgan, Gergel, and Coops 2010).

Satellite imagery contains multiple bands of data representing a range of wavelengths of both visible and non-visible light that can provide more meaningful information about the landscape. The first Landsat satellite was launched in 1972 and remained in orbit until 1978. Landsat 1 only recorded four spectral bands: green, red, and two near infrared bands at 80-m resolution. Landsat 8, launched in 2013 and still in orbit, collects nine unique spectral bands at 30-m resolution including ultra-blue, blue, green, red, near infrared, shortwave infrared 1, shortwave infrared 2, panchromatic, cirrus, thermal infrared 1, and thermal infrared 2 with the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) sensors. Each band represents a single layer of spectral data. The panchromatic band can be combined with other bands to increase the resolution from 30 m to 15 m, a method called pan sharpening. Visual and non-visual bands can be isolated and studied to determine small changes in reflectance, or combined with others to show complex changes in reflectance. For example, high levels of red and near infrared reflectance values indicate healthy vegetation, while thermal reflectance is used to measure heat radiance, often after wildfires (USGS 2015).

Users can manipulate these data layers in various ways depending on the phenomenon under investigation (Roy et al. 2014; Young et al. 2017). For example, a study done in the forests of the eastern Cascades of Oregon used remote sensing of Landsat data to map areas of varying degrees of insect spread and damage exhibited by loss of red and infrared reflectance, indicative of vegetation decline. Spectral patterns were identified that confirmed the presence of species-specific insect disturbance (Meigs, Kennedy, and Cohen 2011).

Simulating Future Wildfire Risk

It is clear that in many places of the eastern Cascades, wildfire risk has become much more extreme compared to historic conditions, and will likely continue to do so in the future. Using historic stand data combined with modern conditions, future growth and mortality of forests can be simulated to estimate future potential fire risk (Reinhardt and Crookston 2003). The Forest Vegetation Simulator (FVS) is used by both government agencies and landowners to predict forest growth, mortality, and current and future risk of disturbance using stand inventory data (Dixon 2013). Within the FVS are variants that represent unique geographic regions in the United States, such as the Eastern Cascades variant (used for this research). The variants contain information regarding local tree species and species-specific equations for tree growth and mortality. The simulator calculates potential stand structure after user-determined intervals of time. A text output file of each stand is created that summarizes structure with variables such as the quantity of each tree species still living, mortality rates, snag abundance, tree diameter distribution, and other user-specified variables (Dixon 2013).

The Fire and Fuels (FFE) Extension contains additional tools to calculate potential flame lengths, the likelihood of torching and running crown fire, and available dead and living fuel volume by allowing the user control over fuel management, weather, and other conditions (Reinhardt and Crookston 2003). The extension does not predict fire events, but rather estimates potential fire type and severity under various weather conditions (Dixon 2013). For management purposes, FVS-FFE also allows the user to prescribe treatments, such as thinning or prescription burning, to the forest to evaluate the effects on fire hazard potential (Ager, Vaillant, and Finney 2011).

In a study spanning much of the western U.S., potential wildfire simulations were run on each of the ponderosa pine- and Douglas fir-dominated stands with and without prior fuel treatments (Ager, Vaillant, and Finney 2011). The study found that stands in the eastern Cascades most highly susceptible to extreme fire behavior benefited the most from fuel treatments, while stands at less risk benefited very little. This type of fire modeling provides research opportunities, otherwise unavailable, to see how disturbances will affect a forest under various conditions.

CHAPTER III: STUDY AREA

Location

The study area for this research is the Teanaway Community Forest, which is located in the upper Yakima Basin of central Washington State, on the eastern slope of the Cascade Range (Figure 1). The Washington State-owned forest encompasses approximately 20,332 hectares of public land. To the north is Mount Stuart and the Okanogan-Wenatchee National Forest, with Interstate 90 to the south. The town of Cle Elum lies approximately 5 km south of the Teanaway Community Forest's southern-most border. The study area ranges from approximately 47.220° to 47.346° N and from -120.746° to -121.021° W.

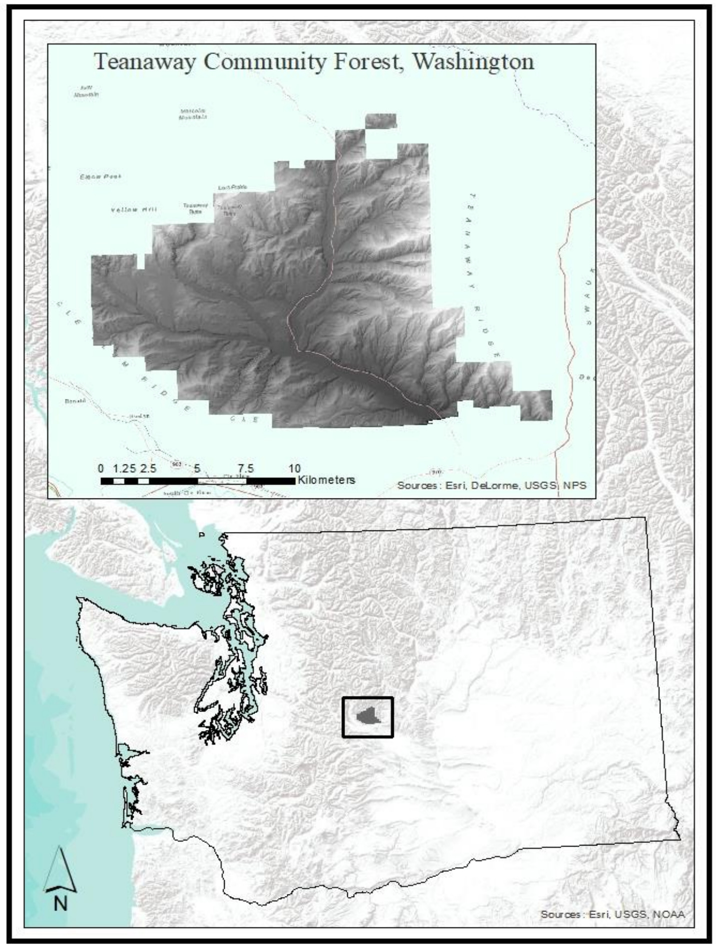

Figure 1 Teanaway Community Forest, Washington

Geology and Geomorphology

The geology of the Teanaway has been shaped by volcanic, tectonic, geomorphic slide, and glacial activity. The bedrock is described as Swauk formation sedimentary sandstone of Eeocene age overlying the Teanaway basalts, and contains Pleistocene glacial outwash and lake deposits (DNR 2015). Elevation varies widely, from approximately 600-1450 m (Wright and Agee 2004). Soils are dominated by the moderately well-drained Teanaway ashy loam. These soils support dry forest vegetation, such as ponderosa pine and Douglas-fir and have formed from glacial and volcanic ash parent material (USDA 2010).

Climate

The Teanaway area has generally warm, dry summers and cold, wet winters, and sits in the rain shadow of the Cascades. The nearby town of Cle Elum receives an average of 560 mm of precipitation per year. Precipitation rates are highest in November and lowest in August (Figure 2). The average maximum temperature reaches 27° C in July, while the average minimum in the winter is -6° C in January (WRCC 2017). Average annual temperature is approximately 8° C. Winds reach an average of over 24 km/hour in July (WRCC 2017). Mean annual snowfall is approximately 2,020 mm per year in Cle Elum (WRCC 2017).

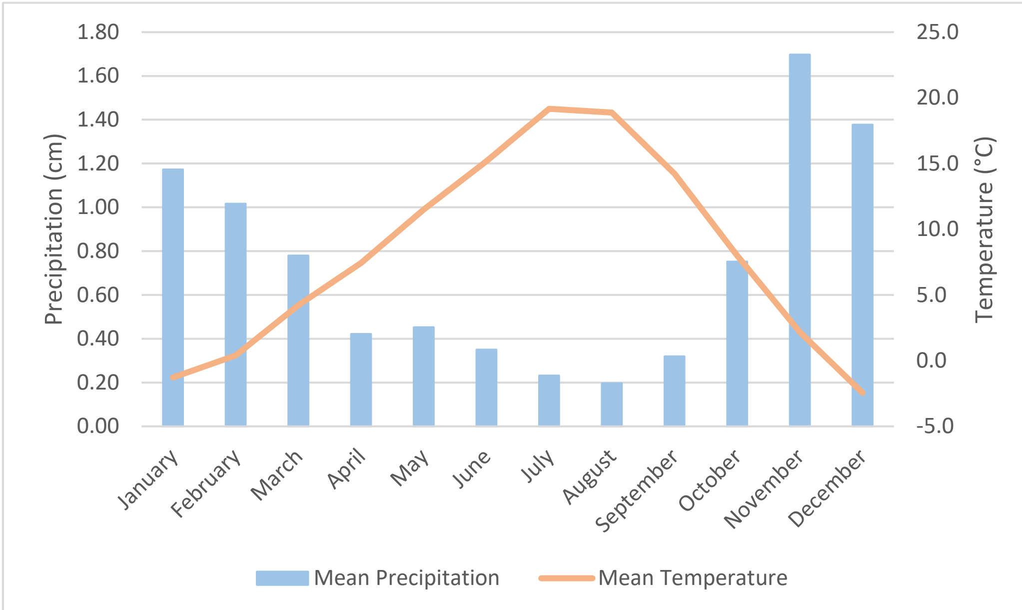

Figure 2 Cle Elum climograph 1981-2010
(Data retrieved from http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?wa1504)

Hydrology

Within the TCF, the West, Main, and North Fork Teanaway rivers join into the main stem of the Teanaway River that then flows into the Yakima River. Highest stream flows occur during May and lowest stream flows are in September (USGS 2014). Due to rising demand, water resources must be distributed per the Yakima Basin Integrated Water Plan (YBIP) (Sandisen, Derek and Christiansen 2012). The YBIP outlines several priority uses for water in the Yakima Basin. For example, irrigation needs are highly valued due to the large agricultural industry in the Yakima Basin, growing population has significantly increased demand for drinking water, and struggling fish populations are an indicator of poor stream health (Sandisen, Derek and Christiansen 2012).

Vegetation

The Teanaway Community Forest encompasses 20,332 hectares of widely ranging terrain. Varying elevation and precipitation levels create a gradient of forest types including ponderosa pine woodland, dry-mesic montane mixed-conifer forest, and mesic montane mixed-conifer forest (Lillybridge et al. 1995). The lower elevation region is characterized by a dry mixed-conifer forest, dominated by ponderosa pine. This tree species generally exists at approximately 600 to 1200 m elevation (J.F. Franklin and Dyrness 1973). Although a significant number of ponderosa pines were historically logged (Hessburg and Agee 2003), their continued presence may be attributed to a combination of natural regeneration and replanting efforts. The other dominant tree species is Douglas-fir and there are various understory plants, such as Idaho fescue (*Festuca idahoensis*), elk sedge (*Carex geyeri*), yarrow (*Achillea millefolium*), and bluebunch wheatgrass (*Pseudoroegneria spicata*). In the Teanaway, encroachment of shade-tolerant Douglas-fir and grand fir (*Abies grandis)* limits the amount of historically open ponderosa pine-dominated stands remaining (J.F. Franklin and Dyrness 1973).

As elevation and available precipitation increases, ponderosa pine-dominated forest transitions into the dry-mesic and mesic montane mixed-conifer forest types (Lillybridge et al. 1995). The forest structure of these is generally more dense and composed of shade-tolerant trees, including Douglas-fir, grand fir, lodgepole pine, and western larch (DNR 2015). Douglas-fir is considered to be the climax species at higher elevations of the TCF. Under the right moisture conditions and in the absence of disturbance, Douglas-fir will eventually dominate the stands in which it is present

(Lillybridge et al. 1995). More detail on current vegetation communities will be in the results section.

Land Use History and Policy

There is significant evidence of Native American land use prior to Euro-American settlement throughout the Pacific Northwest (Pyne 1982; Boyd 1999; Hessburg and Agee 2003; Walsh, Duke, and Haydon 2018). The widespread use of grazing animals by Native Americans dates back to the early 1800s, in addition to intentional burning on the landscape (Pyne 1982; Hessburg and Agee 2003). These surface fires helped keep meadows and forests structurally open and stimulated growth of berries and other edible plants (Hessburg and Agee 2003). Although Native Americans still use land in the TCF in accordance with tradition and under the protection of the Yakama Treaty of 1855 (DNR 2015), settlers began to dominate the landscape with management practices that limited fire in the mid-19th century (Johnson and Swanson 2009).

News of the discovery of gold in Kittitas Valley by surveyor George McClellan in 1853 spread and miners soon arrived, building roads and infrastructure (Glauert and Kunz 1976) that acted as fuel breaks and promoted fire exclusion (Forman and Alexander 1998). Kittitas County became available for homesteading in 1876 (Glauert and Kunz 1976). White settlers also brought with them additional grazing animals and implemented fire suppression policy to the TCF by the 1930s (Haugo et al. 2010). These settlers enacted a policy that allowed Native Americans to be arrested for intentional burning from 1914 to the 1930s (Boyd 1999).

Beginning in 1903, the Teanaway Community Forest was harvested for timber by the Cascade Lumber Company (Henderson 1990). Larger trees were preferentially logged for economic purposes – younger trees grew more quickly and would yield more timber over time (Johnson and Swanson 2009). Logs were primarily transported by way of the Yakima River to the company sawmills located in Yakima, Washington, until 1916 when construction of the railroad was completed. In 1957, the Cascade Lumber Company merged with the Boise Payette Lumber Company, becoming the Boise Cascade Corporation. In 1999, the TCF was purchased by American Forest Lands, a Washington-based timber company and logging activities continued until its purchase in 2013 by Washington State. The TCF was harvested multiple times during the twentieth century (Henderson 1990).

Growing public concern regarding environmental effects of logging and fire suppression during the 1960s and 1970s initiated new forestry policies. Old-growth forests were becoming extremely scarce in the Pacific Northwest because of widespread logging, and wildlife were suffering as a result (Thomas et al. 2006). In 1988, the Northern Spotted Owl (*Strix occidentalis caurina*) (NSO) was listed as endangered by the Washington Fish and Wildlife Commission, and as a Threatened Species in 1990 under the Endangered Species Act of 1973 (Buchanan 2016). The NSO ranges from British Colombia to California, historically residing in dense, old-growth forests of the west coast. The modern overstocked forest structure of the eastern Cascades that is conducive to NSO nesting and foraging and has promoted migration from the west coast is a direct result of fire suppression. However, this forest structure promotes stand-replacing fires, which pose great risk to the species by destroying their habitat (Buchanan 2016), reiterating the need for improved stand management. In 1994, the Northwest Forest Plan (NWFP) was passed as a response to the growing need for the preservation of NSO's and other ecologically significant species associated with old-growth forests (Thomas et al. 2006). Sustainable timber harvest combined with the preservation of old-growth stands that serve as ideal NSO habitat comprise the bulk of the plan. Overall, old-growth forests increased in area, but NSO numbers continued to decrease, likely resulting from competition from the Barred Owl (*Strix varia*), which have expanded into NSO territory in recent years (Buchanan 2016). Other species protected by ESA in the Teanaway include the bull trout (*Salvelinus confluentus*), who spend their lives in headwater streams and are extremely susceptible to drastic changes in temperature and environment for the entirety of their lifespan (Stine et al. 2014). Changes in forest structure can easily affect sensitive species such as these. A study done in Alberta, Canada, examined relationships between bull trout populations and various types of disturbance (Ripley, Scrimgeour, and Boyce 2005). It was found that bull trout declined significantly alongside increases in industrial activities, such as tree harvesting and road-building, that may allow ambient air temperatures to increase above tolerable levels.

The ponderosa pine habitat in the TCF is deemed "critical" by the Washington Department of Fish and Wildlife (WDFW) due to its growing scarcity, and the forest was thus purchased in 2013 to be managed and restored under the DNR and the WDFW as

Washington's first community forest (DNR 2015). Not only is the ponderosa pine forest type becoming more valuable because of logging and Douglas-fir competition (J.F. Franklin and Dyrness 1973), but also the Teanaway watershed is now under state protection for other purposes. The YBIP included the purchase of the Teanaway Community Forest in order to manage its water irrigation, recreation, and valuable fish habitat (DNR 2015).

Study Sites

Stand inventories were acquired from June to October of 2017. Study sites were chosen at random from Wright's (1996) thesis and bounded by the modern boundaries of the TCF. However, many sites were inaccessible due to various obstructions, such as overgrowth of vegetation, private property, and a sizeable wildfire that occurred in the northwest corner of the TCF during August of 2017. The study sites range considerably in elevation, aspect, forest cover type, moisture, and types of disturbance evident (Table 1).

Table 1
Study site characteristics (PIPO: ponderosa pine; MC: mixed-conifer; GF: grand fir; RI: riparian; G: grazing; F: fire; L: logging; D: defoliation)

Site #	Latitude	Longitude	Slope (°)	Elevation (m)	Forest Cover Type	Disturbance
103	47.26	-120.88	4.01	707	RI	G
105	47.29	-120.84	17.62	807	MC	F, G, L
115	47.34	-120.87	10.93	887	GF	F, D
119	47.28	-120.88	1.04	734	PIPO	F, L
121	47.28	-120.89	2.05	763	PIPO	F
122	47.29	-120.89	4.75	777	PIPO	-
124	47.25	-120.91	1.12	715	RI	G
126	47.24	-120.93	26.84	799	GF	F
128	47.25	-120.92	9.33	758	MC	F, L
129	47.27	-121.00	9.36	827	PIPO	F, L
134	47.27	-120.95	3.00	772	MC	F
135	47.27	-120.93	2.18	758	PIPO	L
138	47.32	-120.80	10.68	1051	GF	F, G
153	47.26	-120.91	3.77	702	PIPO	G
154	47.25	-120.88	0.54	711	MC	G, L
161	47.33	-120.85	5.35	856	GF	L
162	47.35	-120.84	25.21	921	GF	-

CHAPTER IV: METHODS

The methods of this research consist of four phases that address each of the four objectives. First, vegetation surveys were conducted to acquire stand inventories of various forest cover types in the TCF. Second, remote sensing methods were used to analyze reflectance properties of the TCF that help identify changes in forest composition, density, and greenness characteristics using stand inventory data as training sites. Third, the FVS-FFE was used to evaluate fire hazard potential of each stand. Fourth, these spatial and non-spatial data were combined to create a 2017 fire hazard potential map of the TCF.

Vegetation Surveys

Stand location and inventory methods were based on Wright's (1996) thesis methods. Wright collected tree stand inventory on 90 sites within historic land survey sections. The 11.4 m radius plots were selected based on a subjective evaluation of the most representative vegetation within each section in addition to extracting tree cores to reconstruct a 450-year fire history of the Teanaway Valley. Seventeen of these 90 sites were surveyed for this study, confined by accessibility.

Elevation, aspect, and geographic coordinates were recorded at each chosen site using a Garmin eTrex device and verified with a Digital Elevation Model of the TCF. The circle plots were flagged using measuring tapes. An inventory of all trees at least 1.5 m in height were recorded and measured in each plot, including species, height, height to ladder fuels, percent live canopy, and diameter at breast height (DBH). Tree height and height to ladder fuels were measured using a laser range finder. Any presence of mistletoe or defoliation on the trees were noted. Percent coverage of understory species was estimated visually in 30-m radius circle plots, consistent with the resolution of Landsat imagery. Evidence of disturbance in the large plot were categorized into fire activity, logging, or grazing, and recorded. This evidence could include the presence of charred snags, burned downed woody debris, logged stumps, or cow droppings indicating any past or current land use purposes.

The presence of downed woody debris was recorded at 3-m intervals on three 30-m long radial transects from the center of each plot directly north, 30 degrees south of east, and 30 degrees south of west. Canopy coverage was also recorded at these intervals using a clinometer.

Remote Sensing Data Acquisition

Multispectral Landsat Level-2 imagery with 30-m pixel resolution from 1984, 2000, 2013 and 2017 were obtained from the U.S. Geological Survey (USGS) remote sensing database GloVis (Global Visualization) Viewer. Level-2 data are absolute surface reflectance images, and are geometrically- and terrain-corrected by the USGS to account for variation in the Earth’s curvature, solar angles, and satellite differences. The images were acquired at approximately the same time of year and were subjectively selected based on best atmospheric clarity with minimal cloud cover and aerosol or smoke conditions (Table 2).

Table 2
Data Source Information

Source	Acquisition Date	Satellite	Projection	Resolution
USGS	1-Jun-84	Landsat 5 TM	UTM WGS 84 Zone 10	30 m
USGS	16-Jul-00	Landsat 7 ETM	UTM WGS 84 Zone 10	30 m
USGS	10-Jun-13	Landsat 8 OLI/TIRS	UTM WGS 84 Zone 10	30 m
USGS	21-Jun-17	Landsat 8 OLI/TIRS	UTM WGS 84 Zone 10	30 m

Preprocessing and Stacking

All images were processed using ERDAS Imagine in the CWU GIS Lab. Image corrections were only utilized if absolutely necessary, as they often introduce additional error (Young et al. 2017). A subset, using the boundaries of the TCF, was extracted and verified from each Landsat scene. Co-registration was verified amongst all subsets allowed for comparison. Because the TCF is of somewhat rugged topography, a Ratio Vegetation Index (RVI), which has been shown to help correct for topographically induced shadows by enhancing vegetation health reflectiveness, was created for each date using the associated near infrared (NIR) and red bands (Eq. 1) (Kao, Ren, and Lee 2014).

$$RVI = \frac{NIR}{Red} \tag{1}$$

A normalized difference vegetation index (NDVI) was then performed for each date (Eq. 2). NDVI is particularly efficient at exposing the difference between red and near infrared reflectance, which is a non-visible indicator of plant vigor, vegetation growth, and biomass (Jensen 2005).

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \tag{2}$$

The blue, green, red, near infrared, shortwave infrared 1, shortwave infrared 2, topographic band ratio, and NDVI layers were then stacked for each of the image datasets, providing a unique spectral signature for each individual pixel (Figure 3).

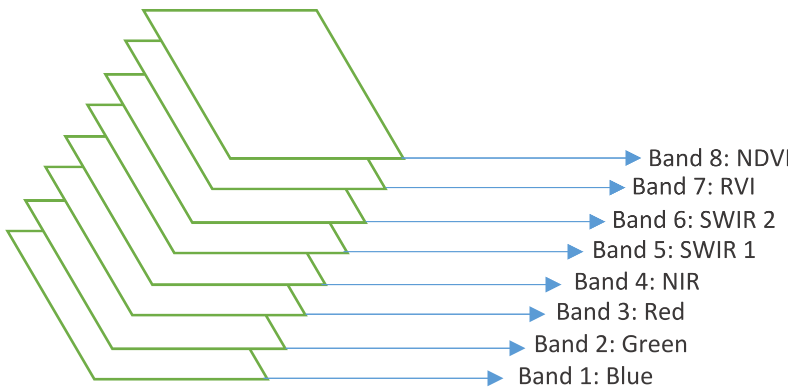

Figure 3 All stacked bands included in each dataset from 1984, 2000, 2013, and 2017.

Classification

A supervised classification was performed using fieldwork plots for spectral training data. Areas of Interest (AOI's) were created around each inventory plot and other easily discernible broad land cover types such as water, pavement or exposed bedrock, and agricultural fields. These spectral signatures were added to the signature editor to create supervised clusters. A parallelpiped algorithm was used to group the spectral signatures, or ordered combinations of digital numbers (DN's) associated with each pixel, into unique forest patch or land cover types. This method is based on similar ranges of

DN values and is less computationally intensive while introducing little additional error (Jensen 2005). Final land cover classifications were identified as riparian, open PIPO, closed mixed-conifer, closed grand fir, water, sparse slopes and dry meadows, and exposed bedrock and pavement (Table 3). Agricultural areas were separated with an AOI and reclassified to zero to exclude them from the analysis.

Table 3
General characteristics of each land cover class used in remote sensing classifications.

Land Cover Class	Characteristics
Rock/Pavement	Bedrock, roads, pavement, structures
Sparse/Xeric	Dry meadows, sparsely vegetated areas
Water	Rivers, lakes
Riparian/Mesic	Mesic wetland areas, commonly vegetated by grasses, cottonwoods, western larch
Overgrown GF	Overstocked grand fir stands with mesic-associated understory such as vine maple, Oregon grape, ferns, GF seedlings
Overgrown MC	Mixed conifer including Douglas-fir, ponderosa pine, some grand fir with grasses and both mesic- and xeric-associated understory
Open PP	Dominated by ponderosa pine and grasses

An NDVI difference function was used to isolate vegetation reflectance change using only the 1984 and 2017 images. This calculates the changes in vegetation reflectance and does not require radiance values for calculations or comparison. Four classes of vegetation change were processed: decrease in vegetation reflectance by more than 10 percent, decrease by less than 10 percent, increase by less than 10 percent, and increase by more than 10 percent. A diagram showing all preprocessing and processing steps is shown in Figure 4.

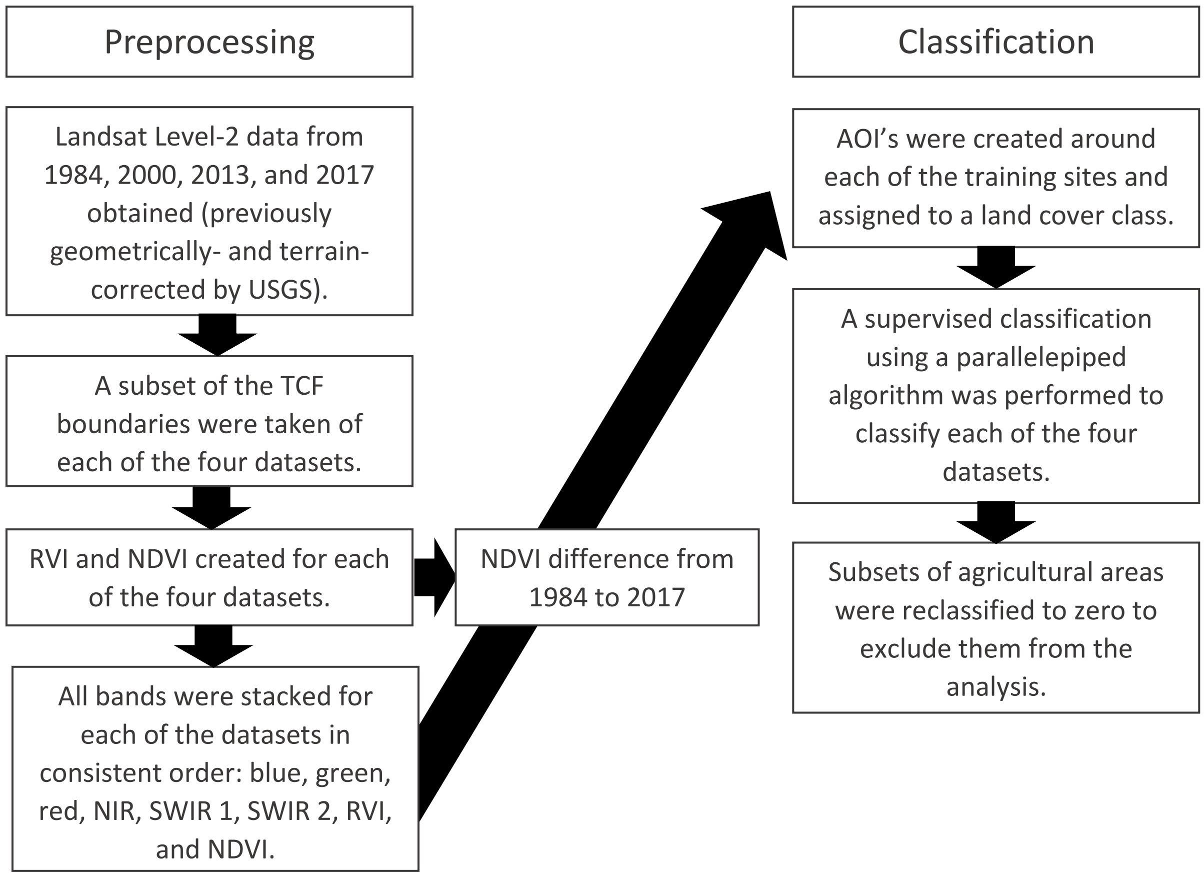

Figure 4 Schematic diagram of processing remote sensing imagery.

Forest Vegetation Simulator

Data for the FVS input file database was obtained from vegetation surveys completed during summer 2017, as described above. A Microsoft Access database containing all tree inventory data was created. The first table contained stand ID, variant, inventory year, coordinates, region code, forest code, location code, potential vegetation code, inventory plot size, aspect, slope, and elevation gives FVS all required geographic and physical information. The second table contained individual tree data, including stand ID, species, dbh, tree height, and living crown ratio. No other management was selected for this study.

The most important aspects determining wildfire severity potential include weather, topography, and parameters of structure, including size class distribution, stand density, composition, and surface fuels (Agee 1996). Because small-diameter trees are less resistant to fire-related mortality, the distribution of tree size classes indicates the overall stand age and fire susceptibility. Trees per acre, if too high, results in density-related mortality. FVS calculates potential flame length, torching index, and crowning index using these variables. Dead surface fuels increase potential flame length, which indicates overall fire intensity. Torching index refers to the minimum wind speed required for a fire to move into the crown, while crowning index refers to the minimum wind speed necessary to sustain a crown fire (Reinhardt and Crookston 2003).

The relationship between wind speed, torching index, and crowning index determines potential fire type (Table 4). Conditions were set to approximately 21 degrees Celsius, a relatively cool summer temperature for the TCF, leading to conservative results. Potential fire type is calculated based on the table below.

Table 4
Fire types based on relationship between wind speed, torching index, and crowning index.

Potential Fire Type	Conditions
Surface Fire	Wind speed ≤ Torching/Crowning Indices
Passive Crown Fire	Crowning Index ≥ Wind Speed ≥ Torching Index
Conditional Crown Fire	Torching Index ≥ Wind Speed ≥ Crowning Index
Active Crown Fire	Wind Speed ≥ Torching/Crowning Indices

Surface fires remain in the understory and do not enter the canopy. Passive crown fire occurs when conditions support torching, but canopy mass is too low or sparse to travel through the crown layer. Conditional crown fire will burn through the canopy layer if ignited but lacks the conditions to torch. Active crown fire will occur if both torching and crowning indices are equal to or lower than current wind speeds and are the most difficult to control and are often the most damaging (Reinhardt and Crookston 2003).

Current Fire Type Potential

An additional supervised classification using a parallelepiped algorithm of the TCF was performed using only the preprocessed 2017 image dataset. AOIs representing study sites were instead assigned to their respective fire types calculated by the FVS, enabling the visualization of non-spatial data (fire hazard potential) in the TCF in 2017.

CHAPTER V: RESULTS

This research describes the changes in composition and structure of the Teanaway Community Forest from 1954 to 2017 and estimates current and future potential fire hazard of various stand types. According to the results, the overall state of the forest has transitioned to one that is much less fire-resilient and much more prone to extreme fire behavior both now and in the future.

Fieldwork

Site ID numbers are consistent with Wright's thesis (1996) (Figure 5). The forest plots vary in both density and composition. Low-elevation sites tend to be of open ponderosa pine cover type with some Douglas-fir, while high-elevation sites tend to be of closed mixed conifer or closed grand fir cover types. Most trees are of small diameter and exceeded recommended density for each forest type (Keyser and Dixon 2013). Evidence of past fire activity, logging, and grazing are present at most sites (Table 5).

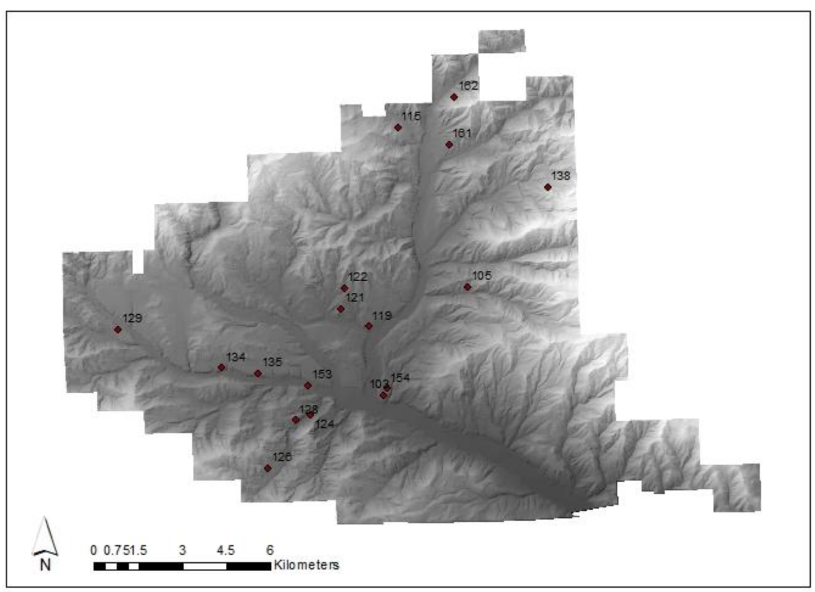

Figure 5 Study sites inventoried throughout the TCF.

Table 5
Overview of study sites (PIPO: ponderosa pine; MC: mixed-conifer; GF: grand fir; RI: riparian; WH: western hemlock; WI: willow; LP: lodgepole pine; AP: aspen; WL: western larch)

Site #	Forest Cover Type	Canopy Cover (%)	Downed Woody Debris (%)	Overstory	Average DBH (m)	Understory*	Evidence of Disturbance
103	RI	47%	20%	37% PIPO 32% DF 16% GF 16% WH	0.12	Grasses	Grazing
105	MC	40%	77%	45% PIPO 25% DF 15% GF 15% WI	0.132	Shrub	Fire, grazing, logging
115	GF	70%	20%	93% GF 2% DF 2% LP 1% AP	0.037	Shrub	Fire, defoliation
119	PIPO	20%	10%	90% PIPO 9% DF 1% GF	0.066	Grasses and shrub	Fire, logging
121	PIPO	23%	43%	88% PIPO 10% DF 3% GF	0.100	Grasses and shrub	Fire
122	PIPO	17%	53%	96% PIPO 4% GF	0.125	Grasses and shrub	N/A
124	RI	63%	23%	37% GF 25% DF 19% WL	0.165	Grasses and shrub	Grazing
126	GF	30%	27%	49% GF 27% PIPO 22% DF 2% MH	0.042	Grasses, shrub, and herbaceous	Fire
128	MC	43%	70%	42% GF 42% DF 16% PIPO	0.108	Grasses	Fire, logging
129	PIPO	23%	50%	58% PIPO 25% LP 17% GF	0.134	Grasses	Fire, logging
134	MC	70%	70%	41% DF 32% PIPO 27% GF	0.267	Grasses	Fire
135	PIPO	20%	53%	68% GF 21% PIPO 9% DF	0.197	Grasses and shrub	Logging
138	GF	57%	30%	78% GF 22% PIPO	0.142	Grasses, shrub, and herbaceous	Fire, grazing
153	PIPO	7%	0%	100% PIPO	0.114	Grasses	Grazing
154	MC	20%	63%	79% DF 15% PIPO 6% GF	0.218	Herbaceous	Grazing, logging
161	GF	30%	60%	52% DF 24% PIPO 21% GF 3% WI	0.349	Grasses	Logging
162	GF	90%	93%	100% GF	0.237	Shrub	N/A

*Understory is described based on dominant vegetation type of at least 30% cover (unless there are no dominant types, then all types present are listed). See Appendix B for a detailed list of understory species.

In total, there are five plots densely populated by grand fir and other shade-tolerant species, four stands dominated by mostly ponderosa pine and Douglas-fir, six slightly more open sites of mixed species, and one riparian site. Almost all sites are heavily dominated by small-diameter trees regardless of species (Figure 6). Canopy cover is extremely varied, tending to be much higher in grand fir and mixed-conifer stands and lower in PIPO stands (Figure 7).

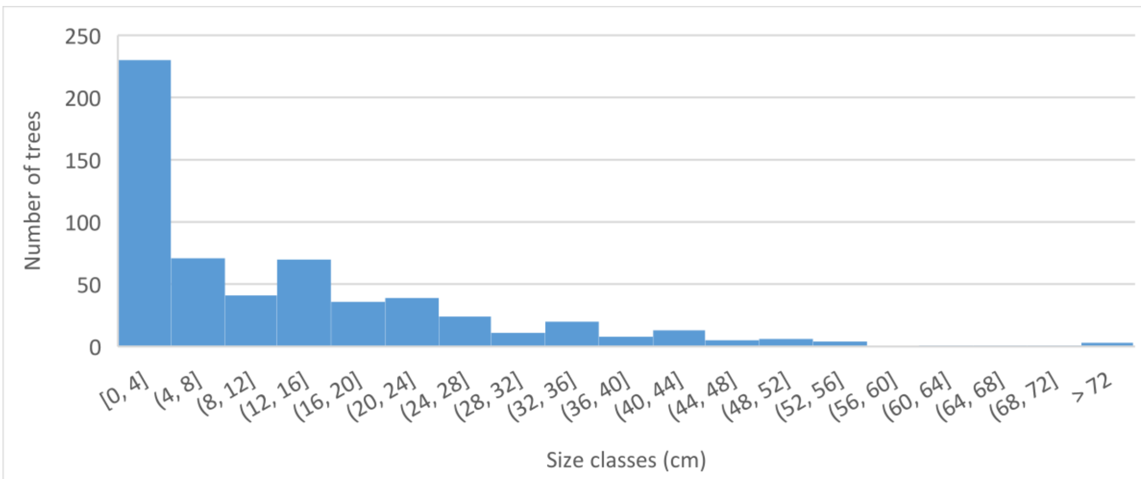

Figure 6 Diameter size class distribution of trees from all inventory plots within the TCF in 2017.

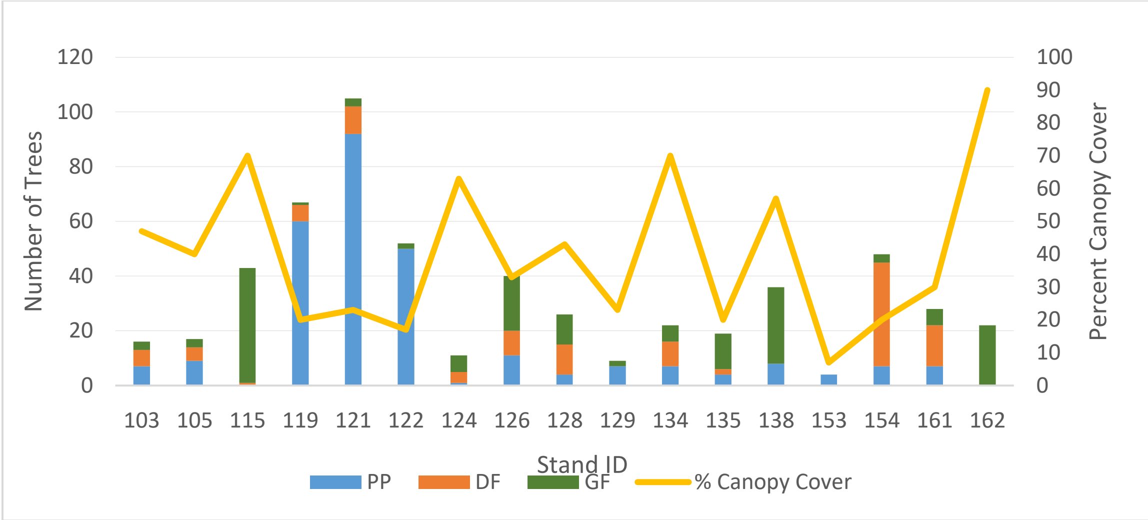

Figure 7 Dominant species distribution and percent canopy cover by field site in 2017.

Land Cover Trajectory

Supervised classification of the images showed a steady increase in area of the closed grand fir forest class over time (Figure 8), indicating the consistent spread of dense, grand fir-dominated stands. Mixed-conifer stands decreased, while ponderosa pine stands fluctuated slightly but ultimately decreased over the 31-year period.

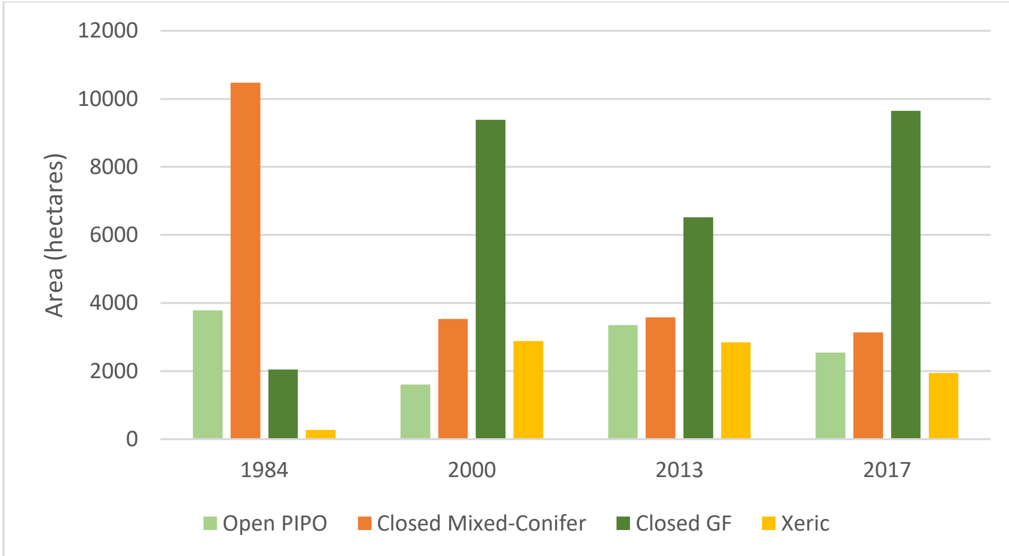

Figure 8 Results of a supervised classification of the TCF by area of dominant land cover classes from 1984 to 2017 (hectares).

In 1984, just over 10,000 hectares were dominated by dense ponderosa pine and Douglas-fir-dominated stands (Figure 9). Only 2,000 hectares of dense grand fir class existed and was isolated to the upper elevation areas of at least 900 m. Xeric, sparsely vegetated area encompassed less than 500 hectares total. Bedrock was exposed throughout much of the TCF.

In 2000, closed mixed-conifer forest fell to approximately 3,500 hectares, while the grand fir class increased from 2,000 to over 9,000 hectares of coverage. Ponderosa pine forest area fell from almost 4,000 to 1,600 hectares. Sparsely vegetated area rose to almost 3,000 hectares.

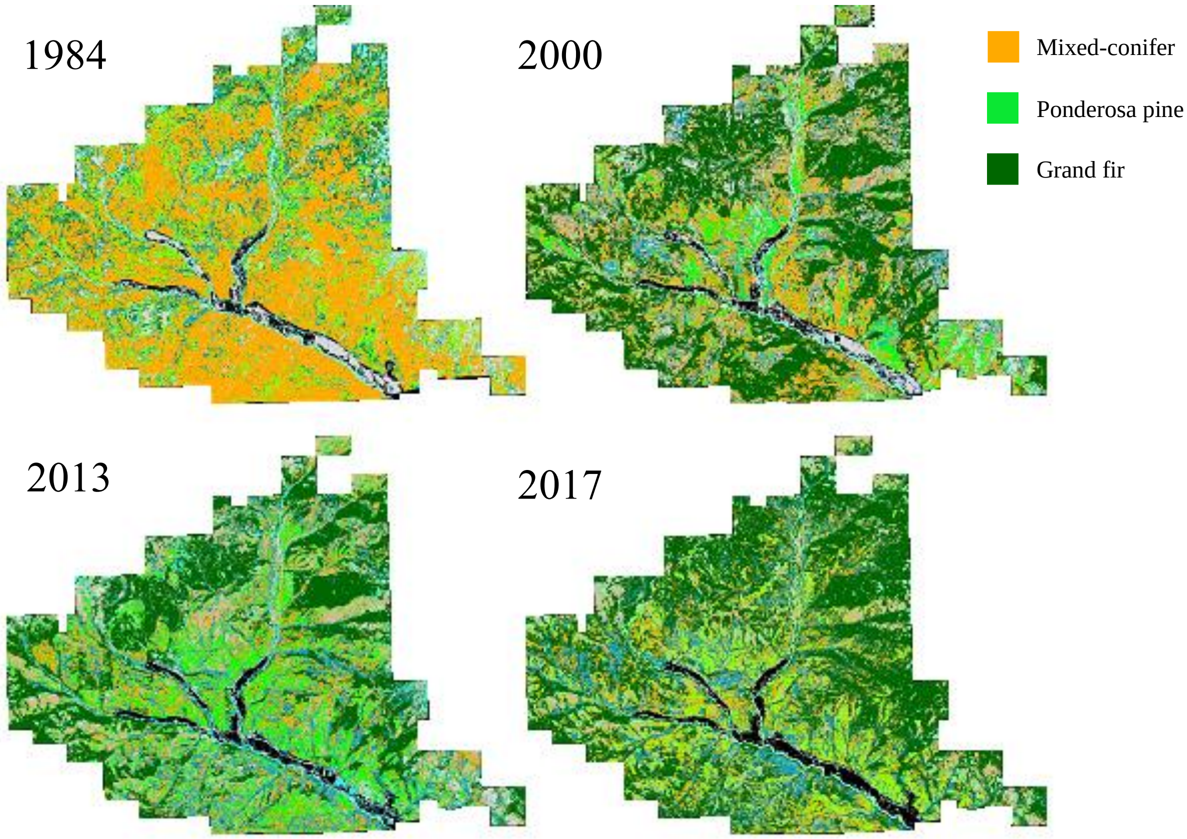

Figure 9 Supervised classification results of the TCF
in 1984, 2000, 2013, and 2017.

The 2013 data showed a decrease in grand fir-dominated stands from over 9,000 to 6,500 hectares. The bedrock class decreased in mid- to upper-elevation areas from approximately 800 m and was encroached upon by grand fir and riparian classes. The riparian class increased in area from over 1,200 to over 3,000 hectares, mostly concentrated in upper elevation areas from approximately 850 to 950 m along creeks and amongst the grand fir class.

From 2013 to 2017, land cover classes indicated an increase in grand fir-dominated areas from 6,500 to 9,600 hectares on northern-facing slopes and high-elevation areas of at least 800 m encroaching into previous sparsely vegetated or ponderosa-pine dominated land cover classes. Mixed-conifer stands decreased slightly. Ponderosa pine stands fell from 3,300 to just over 2,500 hectares as patches became intruded and replaced by mixed-conifer and grand fir classes. Some sparsely vegetated dry meadows still exist, concentrated on southern-facing slopes. Much of the riparian class in the high-elevation areas was overtaken by the grand fir class, but increased along creeks and rivers at about 600-700 m in elevation.

The NDVI difference between 1984 and 2017 showed much of the study area having high DN values, indicating significant increases in vegetation reflectance. Large increases in vegetation reflectance occurred mostly in higher elevations from approximately 900-1200 m and on north-facing slopes (Figure 10). An image highlighting

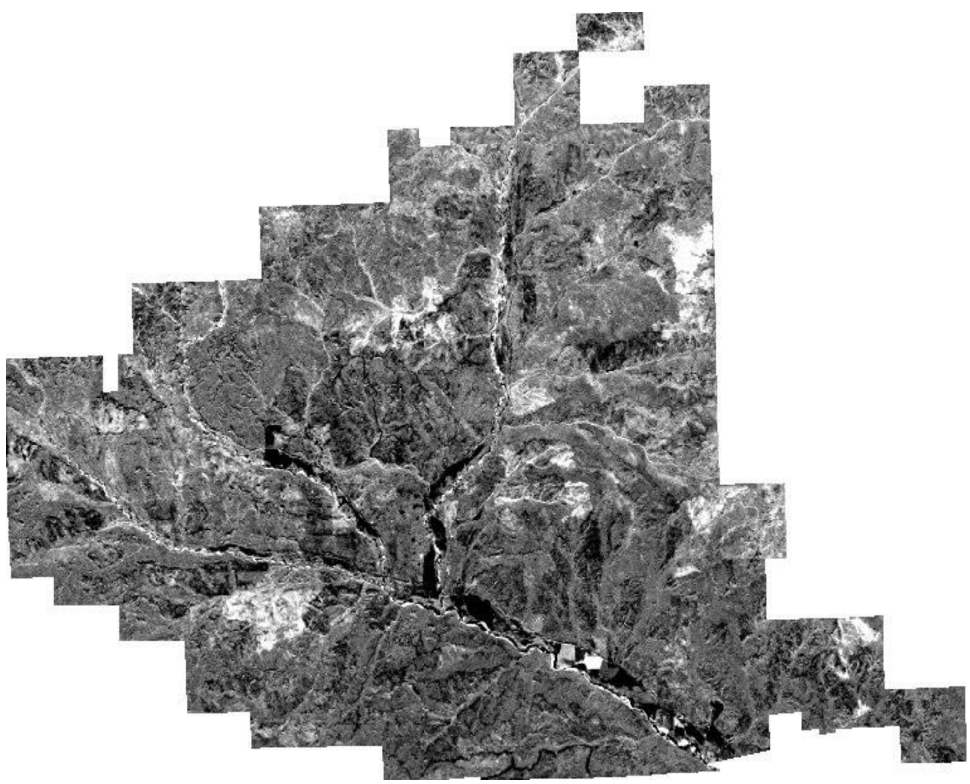

Figure 10 NDVI difference image from 1984 to 2017.

four categories of change (greater than 10 percent increase, less than 10 percent increase, greater than 10 percent decrease, and less than 10 percent decrease) shows that most of the study area, over 16,000 hectares, experienced at least 10 percent vegetation reflectance growth while decreases in vegetation of at least 10 percent were isolated mostly to designated agricultural areas (Figure 11). Other areas of vegetation reflectance decrease seem to have occurred in areas where logging roads,

road junctions, and houses or other structures have been built. The area attributed to a greater than 10 percent increase in vegetation reflectance over this period reached over 16,000 hectares. Pixels attributed to any increase at all reached 4,500 hectares. Less than 1,300 hectares indicate any decrease in vegetation reflectance (Figure 12).

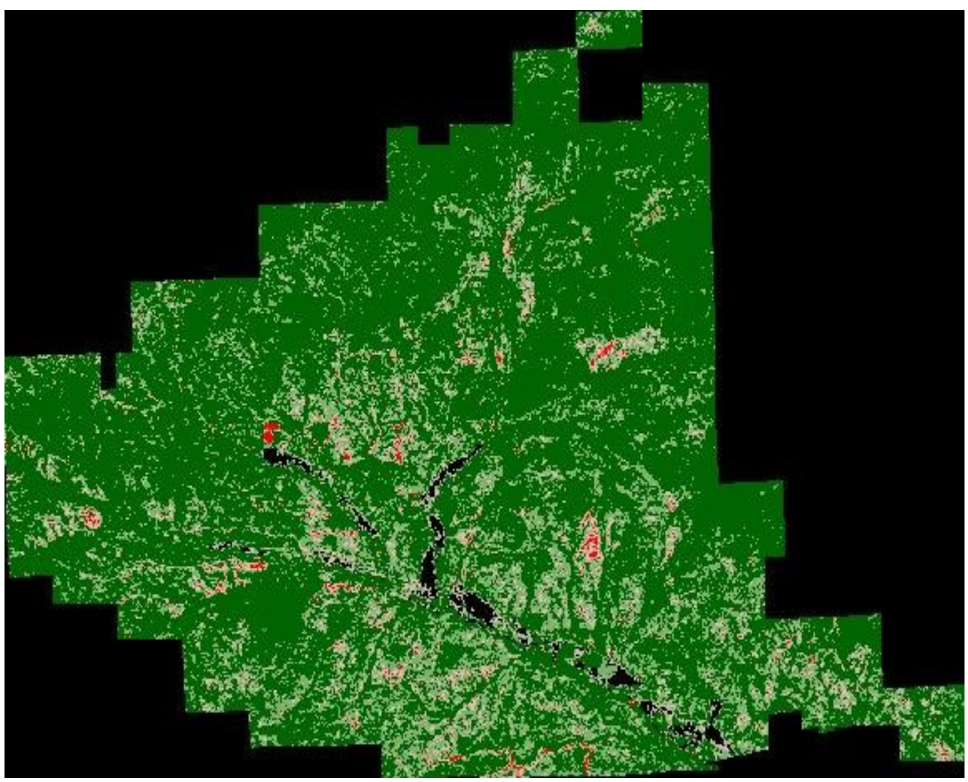

Figure 11 NDVI difference image from 1984 to 2017, highlighting four categories of change.

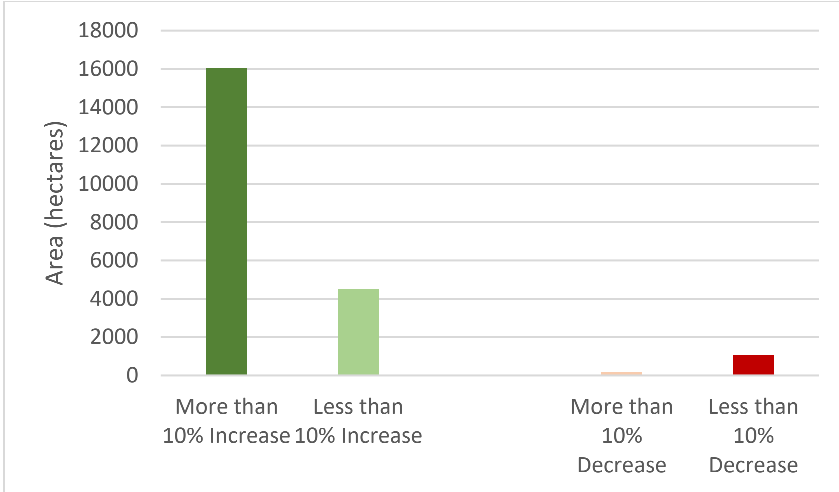

Figure 12 Change in vegetation reflectance (hectares) based on NDVI's from 1984 to 2017.

Forest Vegetation Simulator

Simulations of the TCF under a no management scenario showed significant increases in fire hazard during the next century based on three main variables. Potential flame lengths of all sites except site 153, which was an extremely sparse ponderosa pine-dominated site, increased consistently through all time increments (Figure 13). Especially large increases in potential flame lengths occurred at sites 121, 128, 154, 161, and 162 (Table 6), three of which are grand fir classes, one mixed-conifer, and one ponderosa pine.

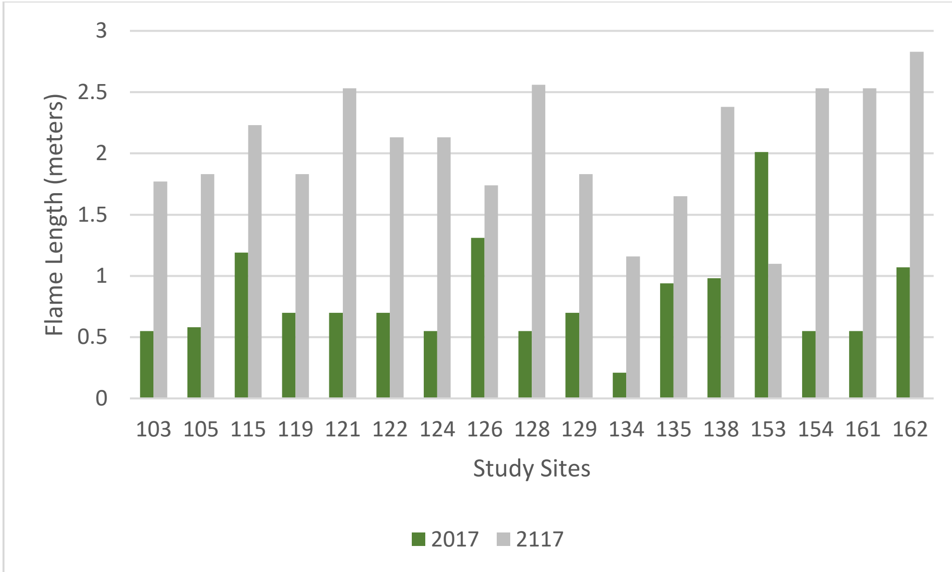

Figure 13 Potential flame lengths (m) of all sites under "severe" weather conditions i.e. 21 degrees C and 32 km/hr wind speeds from 2017 to 2117.

Table 6
Potential flame length of each site at ten-year increments (m).

	103	105	115	119	121	122	124	126	128	129	134	135	138	153	154	161	162
2017	0.55	0.58	1.19	0.7	0.7	0.7	0.55	1.31	0.55	0.7	0.21	0.94	0.98	2.01	0.55	0.55	1.07
2027	0.73	0.88	0.76	1.22	1.8	2.1	0.73	0.73	0.88	1.04	0.46	1.25	1.92	1.83	2.04	1.46	1.74
2037	1.07	1.31	0.98	1.55	2.5	2.44	0.98	1.07	1.68	1.43	0.98	1.52	2.47	1.65	2.53	1.98	2.83
2047	1.34	1.49	1.19	1.71	2.53	2.53	1.19	1.4	2.01	1.74	1.16	1.68	2.59	1.19	2.53	2.29	2.83
2057	1.52	1.65	1.58	1.77	2.53	2.53	1.43	1.71	2.23	1.83	1.22	1.77	2.59	0.79	2.53	2.44	2.83
2067	1.68	1.74	1.77	1.8	2.53	2.5	1.55	1.83	2.32	1.86	1.22	1.8	2.59	0.85	2.53	2.53	2.83
2077	1.68	1.77	1.92	1.83	2.53	2.44	1.77	1.89	2.44	1.95	1.22	1.8	2.59	0.94	2.53	2.56	2.83
2087	1.71	1.77	1.98	1.86	2.53	2.35	1.92	1.86	2.5	2.01	1.19	1.8	2.59	1.01	2.53	2.56	2.83
2097	1.71	1.86	2.19	1.86	2.53	2.29	1.89	1.86	2.56	1.92	1.16	1.77	2.56	1.07	2.53	2.56	2.83
2107	1.77	1.83	2.16	1.86	2.53	2.19	2.01	1.8	2.56	1.86	1.16	1.71	2.47	1.1	2.53	2.56	2.83
2117	1.77	1.83	2.23	1.83	2.53	2.13	2.13	1.74	2.56	1.83	1.16	1.65	2.38	1.1	2.53	2.53	2.83

Torching indices vary quite widely (Table 7). For sites 103 and 124, both of which are classified as riparian, torching index ranges from approximately 60 to 370 km/hr over the next century, beginning in the lower range and increasing rapidly in 2047. Closed mixed-conifer forest classes, including sites 105, 128, 134, and 154, have torching indices slightly lower, ranging from 0 to almost 400 km/hr. Several of these sites begin high, decrease to zero between 2037 to 2067, then rise again thereafter. Open ponderosa pine forest classes, including sites 119, 121, 122, 129, 135, and 153, vary from 0 to about 260 km/hr, with some remaining lower throughout the time period and others rising slowly but consistently through time. By far the most variable torching index values belong to the closed grand fir forest class, ranging from 0 to almost 400 km/hr, including sites 115, 126, 138, 161, and 162. Some sites decrease to zero or almost zero after several decades. Site 161 begins high then drops immediately, and site 162 begins the simulation at 62.1 km/hr then increases to 398 km/hr.

Table 7
Torching index of each site at ten-year increments (km/hr).

	103	105	115	119	121	122	124	126	128	129	134	135	138	153	154	161	162
2017	68.1	186	17.2	25.9	60.2	25.4	68.2	0	148	0	268	41.7	40.2	10.5	68.2	68.2	62.1
2027	80	207	2.09	8.37	6.28	0	58.1	15.9	85.3	18.2	138	24.9	7.08	19.5	0	0.64	55.2
2037	49.4	88.2	9.5	21.7	0	0	38.1	11.1	55.2	18.5	65	35.9	3.06	6.12	0	1.29	33.3
2047	60.4	83.9	6.44	14.8	0	0	9.01	0	129	25.4	98.5	40.7	0.8	14.8	9.82	4.35	76.6
2057	0	80	4.67	17.7	0	3.06	11.4	0	175	38.5	101	47.5	0.8	33.2	25.9	11.4	124
2067	0	86.9	12.4	16.6	0	10.1	0	0	226	0	114	57.5	0.8	30.3	39.8	19	185
2077	0	0	17.1	20.8	0	15.1	9.17	0	280	0	135	62.6	0.8	26.1	58.1	28.8	240
2087	0	0	0	19.6	0	24.6	10.5	0	301	3.86	168	187	0.8	21.4	81.6	43	293
2097	0	0	0	24.3	0	27.2	0	0	337	0	193	238	1.77	18.4	106	53.9	331
2107	0	0	0	30.4	0	34	0	0	0	2.41	219	254	3.06	18	137	65.3	364
2117	0	0	0	49.4	0	41.2	5.47	0	0	8.85	252	264	9.01	17.4	164	73.4	398

Crowning index remains relatively low across all sites for all time increments (Table 8). Riparian sites have crowning indices ranging from approximately 24 to almost

50 km/hr throughout all time increments. The closed mixed-conifer forest class experiences slightly lower crown indices, from 14 to 26 km/hr. Open ponderosa pine stands range much more widely, from 14 to almost 70 km/hr. Closed grand fir stands have crowning indices ranging from 14 to 55 km/hr.

Table 8
Crowning index of each site at ten-year increments (km/hr).

	103	105	115	119	121	122	124	126	128	129	134	135	138	153	154	161	162
2017	28.8	16.9	28.5	14.3	14.3	14.3	35.4	15.9	15	14.2	14.3	14.3	14	34.1	14.3	14.3	12.4
2027	26.7	19.3	22.1	14.3	14.3	14.3	34.6	13.8	15.1	14.2	14.3	14.3	14	30.1	14.3	14.3	12.4
2037	26.1	22.1	20.8	14.3	14.3	14.3	38.8	17.9	16.3	17.5	14.3	14.3	14	27	14.3	14.3	12.4
2047	27.2	24.6	21.6	14.3	14.3	14.3	41.2	23.8	18.4	26.7	14.3	14.3	14	26.7	14.3	14.3	12.4
2057	26.7	26.4	22.4	14.3	14.3	14.3	42.3	29.6	19.3	34.1	14.8	14.3	14	27.8	14.3	14.3	12.4
2067	25.1	25.3	24	14.3	14.3	14.3	41.8	35.4	20.6	33.3	16.1	14.3	14	28.7	14.3	14.3	12.4
2077	23.7	23	26.1	14.3	14.3	14.3	42.5	40.4	20.8	38.5	16.6	14.3	14	31.1	14.3	14.3	12.4
2087	24	23.5	28.3	14.3	14.3	14.3	44.4	45.2	22.7	43.8	15.9	14.3	14	33.8	14.3	14.3	12.4
2097	24.6	24	31.2	14.3	14.3	14.3	45.2	47.8	24.6	46.5	15.3	14.3	14	35.4	14.3	14.3	12.4
2107	25.3	23.7	32	14.3	14.3	14.3	45.9	45.5	24.8	49.9	15.1	14.3	14	34.6	14.3	14.3	12.4
2117	25.4	24.3	34	14.3	14.3	14.3	46.8	43.3	26.4	52.5	15.5	14.3	14	33.8	14.3	14.3	12.4

Under what FVS determined to be severe fire weather conditions, riparian site 103 is classified as a conditional crown fire with 100 percent mortality rate for all time increments (Table 9). At site 124, also riparian, a surface fire is to be expected with a 15 percent mortality rate in 2017 that decreases consistently and reclassifies to passive crown fire by 2117.

Closed mixed-conifer sites 105, 128, and 134 should experience conditional crown fires over the next century with 100 mortality rates. Site 154 classified as conditional crown fire in 2017, then active crown fire from 2027 to 2057, and back to conditional crown fire thereafter with 100 percent mortality rates throughout.

The forest class open ponderosa pine sites 119, 122, and 135 are estimated to experience active crown fire for almost the entirety of the simulation period. Mortality rate is predicted to be 100 percent. Site 121 predicts conditional crown fire in 2017, then active crown fire thereafter with 100 percent mortality rate. Site 129 is classified as active crown fire for the first four simulations, then surface fire thereafter. Mortality begins at 100 percent in 2017 then decreases notably after the fire type transitions. Site 154 is predicted to experience conditional crown fire in 2017, then active crown fire for the next four decades, and then transitions back to conditional crown fire with 100 percent mortality throughout the simulation.

The closed grand fir site 115 is predicted to experience active crown fire for the first six decades before transitioning to surface crown fire with 100 percent mortality rate for most of the simulation period. Site 126 begins with active crown fire and 100 percent mortality before slowly transitioning to lower-severity conditions. Site 128 is expected to experience conditional crown fire in 2017 then remains at active crown fire thereafter with 100 percent mortality throughout. Sites 161 and 162 are both predicted to experience conditional and active crown fires throughout the simulation with 100 percent mortality rates.

Table 9
Fire type based on relationship between wind speed and fire indices
(S = surface fire; P = passive crown fire; C = conditional crown fire; A = active crown fire).

	103	105	115	119	121	122	124	126	128	129	134	135	138	153	154	161	162
2017	C	C	A	A	C	A	S	A	C	A	C	C	C	P	C	C	C
2027	C	C	A	A	A	A	S	A	C	A	C	A	A	A	A	A	C
2037	C	C	A	A	A	A	S	A	C	A	C	C	A	A	A	A	C
2047	C	C	A	A	A	A	P	A	C	A	C	C	A	A	A	A	C
2057	A	C	A	A	A	A	P	A	C	S	C	C	A	C	A	A	C
2067	A	C	A	A	A	A	P	P	C	P	C	C	A	A	C	A	C
2077	A	A	A	A	A	A	P	P	C	P	C	C	A	A	C	A	C
2087	A	A	A	A	A	A	P	P	C	P	C	C	A	P	C	C	C
2097	A	A	A	A	A	A	P	P	C	P	C	C	A	P	C	C	C
2107	A	A	A	A	A	C	P	P	A	P	C	C	A	P	C	C	C
2117	A	A	P	C	A	C	P	P	A	P	C	C	A	P	C	C	C

Fire Hazard Potential Map

Combining traditionally non-spatial FVS data using remote sensing signatures classifications exhibit widespread potential for severe wildfire behavior in the TCF in 2017 (Figure 14). The TCF is at risk for conditional crown fire potential in over 9,000 hectares. Active crown fire is exhibited by over 5,000 hectares. Passive crown fire is almost nonexistent in the TCF with less than 16 hectares, scattered within very sparsely vegetated areas. Surface fire is represented by almost 3,000 hectares in the TCF (Figure 15). The remaining areas are classified by bedrock, very sparsely vegetated areas, or water.

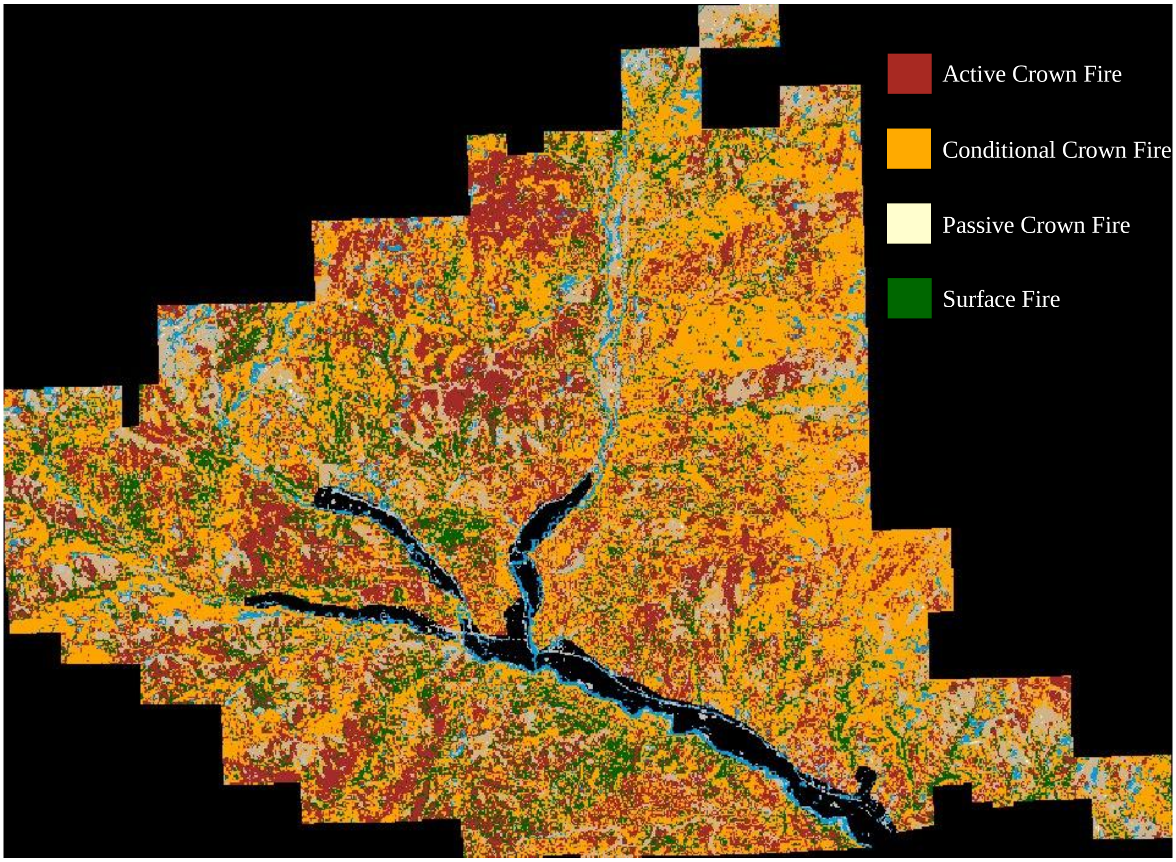

Figure 14 Fire risk map of the TCF in 2017. Much of the TCF is currently at risk for conditional or active crown fire.

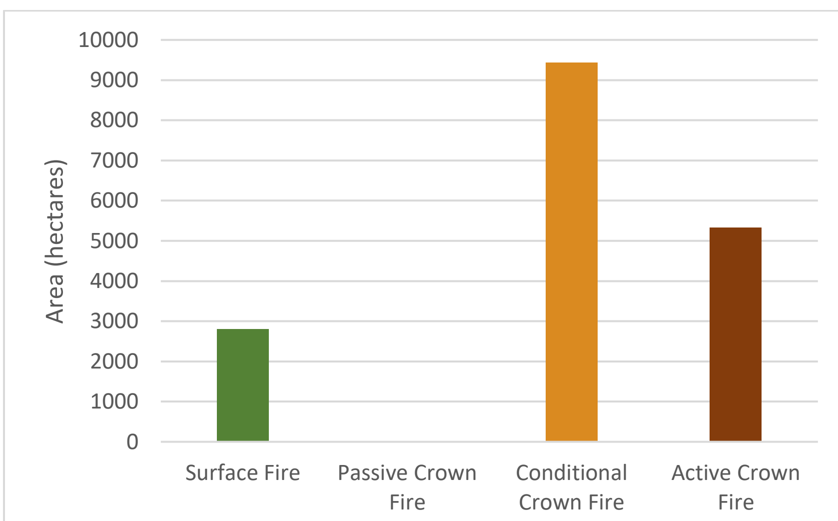

Figure 15 Number of hectares attributed to each category of wildfire behavior potential in 2017.

CHAPTER VI: DISCUSSION

Forest Composition and Structure through Time

Inventories of various stand types throughout the TCF show a dominance of late-seral stage forest types, including overstocked grand fir and mixed-conifer. According to previous historic forest composition reconstructions using GLO records, the TCF was composed of relatively open, early seral-stage forest structure that experienced frequent fire, primarily in ponderosa pine-dominated stands, prior to 1900 (Wright and Agee 2004). Changes in land use has resulted in altered forest composition and structure of the TCF during the last century. The building of roads, thinning of large-diameter ponderosa pines, grazing of fine, connective fuels, and both fire exclusion and suppression by Euro-American settlers has led to a systematic transition from the historic to current forest composition and structure.

The results of these land use changes were reflected in the Wright and Agee (2004) fire history reconstructed using dendrochronological methods, in which both fire frequency and area burned decreased drastically during the last century. Low-severity fires larger than 4000 ha became almost nonexistent in the early 1900s, likely due to the construction of various types of fire breaks, such as railroads and logging roads. Fire suppression, among other practices, has allowed late-seral stage forest composition and structure to ensue, which in the case of the TCF has resulted in the dominance of tree species with little or no adaptations to fire. Even tree species well suited to survive low-to mixed-severity fires lack the space and sunlight to reach maturity and may be killed before these defenses are able to manifest. As such, almost half of all trees measured in all sites were in the 0-4 cm diameter range and less than 20 trees total exceeded just 44 cm (Figure 6).

The lack of adaptations to fire in a species so dominant in the TCF as grand fir is crucial to the overall structure of the forest. Grand fir is highly tolerant of shaded conditions, allowing sprouting even in overstocked areas (Lillybridge et al. 1995). Thick ladder fuels encourage fire to easily transition from a surface to a crown fire. Large and contiguous tree crowns allow for highly dangerous running crown fires. High fuel continuity coupled with hot and dry conditions common in late summer increases the fire potential tremendously and can result in widespread mortality (Agee 1996). Referring to Figure 7, stands with higher proportions of grand fir also reflect high rates of canopy coverage, including sites 115, 124, 126, 128, 138, and 162. The sites near roads and ranging in elevation from approximately 200-800 m had the lowest rates of canopy coverage and tended to be dominated by ponderosa pine, exemplified in sites 119, 121, 122, and 153.

Forest Composition Distribution

Compositional changes in the TCF over the last 33 years are a result of human use of the landscape. The significant increase in grand fir coverage from 2,000 ha in 1984 to over 9,000 ha in 2000 suggest that a lack of frequent disturbance and the harvesting of other species has encouraged the forest to progress to later seral stages. The distribution of grand fir coverage dipped slightly between 2000 and 2013 to under 7,000 ha, likely due to a wildfire in central TCF in 2005, before increasing again in 2017 to almost 10,000 ha. A simultaneous loss of dry meadows can likely be attributed to grand fir encroachment due to the lack of fire, and an increase in the riparian land cover class is likely promoted by the simultaneous increase in the mesic, shade-tolerant grand fir species. Decreasing exposed bedrock is likely due to growing canopy coverage from nearby trees.

The mixed-conifer forest type is highest in 1984 by far at over 10,000 ha, before decreasing tremendously by 2000 to approximately 3,500 ha and remaining somewhat steady until 2017. Harvesting of ponderosa pines and the subsequent spread of grand fir in high-elevation areas has likely encouraged this. Ponderosa pine coverage decreased from almost 4,000 ha in 1984 to less than 2,000 ha in 2000 as a result of logging, before increasing slightly by 2013. The fire that burned in central TCF in 2005 likely cleared some of the small-diameter trees and understory and prompted a small increase in the ponderosa pine class just north of West Fork Teanaway Road.

In the four years following the purchase of the TCF by DNR, grand fir coverage increased by over 3,000 hectares while all other classes decreased. From 1984 to 2017, the TCF increased in vegetation reflectance by at least 10 percent almost in its entirety. Lack of fire to open up the forest, grazing of fine fuels that would otherwise carry fire throughout, and logging of fire-adapted species have all contributed to these changes (Agee 1996; Hessburg and Agee 2003; Haugo et al. 2010). Because the forest was no longer being logged for commercial purposes, and rather, utilized as a multi-use resource (i.e. recreation, logging, and grazing), progress toward late-seral stage forest composition was allowed to continue.

Fire Hazard Potential

Referring to figure 15, the FVS indicates that the TCF is dominated by the potential for conditional crown fire and seconded by active crown fire under modest summer weather conditions of 21° C and 32 km/hr winds in 2017. This is especially true in upper elevation areas, which are dominated by the grand fir class. Passive crown fire is almost entirely nonexistent, largely due to the contiguous canopy layers found throughout most of the forest. Surface fire potential is minimal and occurs in areas where the forest thins out into dry meadows in areas less than approximately 400 m in elevation.

Because conditional crown fire is structurally dependent on the crown layer, it is clear that much of the TCF has either large or numerous connective tree crowns, regardless of tree density. This is slightly less hazardous than active crown fire, which has the ability to turn a surface fire into a running crown fire alongside ideal weather conditions or topography. However, summer conditions in the TCF have reached an average of 27°C in July over the last 30 years (Figure 2), which could potentially shift the conditional crown fire class to active crown fire. Grand fir sites 115 and 126 were classified as active crown fire due to high tree density and vertical fuel continuity. Ponderosa pine sites 119, 122, and 129 were also classified as active crown fire in 2017.

Site 129 is very steeply sloped with 50 percent downed woody debris cover contributing to surface fuels, and sites 119 and 122 had high tree densities and were characterized as extremely dry sites. Site 153 is simulated as passive crown fire due to the extremely low tree density. All other sites are simulated as only conditional crown fire either due to higher levels of moisture, as in the riparian and upper-elevation grand fir sites, or have slightly lower tree densities and ladder fuels. There are numerous variables at play here, any of which could shift the conditional crown fire classification to active crown fire.

The potential flame lengths simulated in the FVS increase as much as fivefold at some sites during the next century due to a build-up of surface, ladder, and crown canopy fuels. Site 128 increased from 0.55 m in 2017 to 2.56 m. Only at site 153 does potential flame length decrease, likely because the open conditions would allow the few ponderosa pines at this site to grow much larger and taller during the next century. Ladder fuels would be out of reach and very few seedlings would establish, leaving little fuel in the future to support more intense fires. In all other cases, downed woody debris, shedding ladder fuels, establishing seedlings, developing understory and trees succumbing to senescence would all contribute to higher potential flame lengths in the future.

Torching index, referring to the minimum wind speed required for a fire to reach the crown layer of a tree, is an important indicator of fire severity and potential mortality (Reinhardt and Crookston 2003). In riparian sites, these numbers tend to be quite high, suggesting moisture levels that would not support intense fire. Grand fir forest types experience highly variable torching indices over time in this simulation. Sites 115, 126, and 138 begin with low torching indices, before decreasing rapidly to as low as 0 km/hr.

These sites are highly overstocked, and the steady decrease in minimum wind speeds can likely be attributed to continued seedling establishment in shady and moist conditions and a continuously developing understory. Sites 161 and 162 both have extremely high torching indices. These sites also have the second and third highest elevations and are much more moist environments, indicated by mesic understory species including lupine (*Lupinus*), Oregon grape (*Mahonia aquifolium*), and several types of ferns. Closed mixed-conifer type stands experience high torching index speeds for the first twenty years of the simulation before falling dramatically in 2037, likely due to surface fuel loading as conifers shed branches. The torching index rises again as the trees grow and the height to ladder fuels increases, making torching more difficult.

The ponderosa pine class experiences relatively low torching indices throughout the simulation. Some stands rise slightly over time due to trees reaching maturity. Ponderosa pine trees shed lower branches specifically as a fire adaptation to discourage torching, but this is only effective in historically open forests with sparse understories and large-diameter trees (Fitzgerald 2005). Overgrown ponderosa pine stands may experience the opposite effect, as small-diameter trees shed branches over time, contributing to surface fuels that are not intermittently cleared by frequent fire.

Crowning index is another indicator of potential fire type, and determines minimum wind speed necessary for a sustained crown fire (Reinhardt and Crookston 2003). This index is consistently low throughout all study sites and seems to depend on moisture availability and canopy coverage. The riparian sites, 103 and 124, are simulated to experience anywhere from 24 to 50 km/hr indices due to both moisture and relatively open tree structure. Grand fir forest types are simulated to have low crowning indices when canopy coverage and tree density is very high, which includes sites 138, 161, and 162. Site 115 has a slightly higher crowning index throughout time in spite of its density, but many of the trees are less than three meters tall. Present at the site are burned stumps and scattered pieces of charcoal, which is indicative of recent fire activity and subsequent reseeding of the area, resulting in a new even-aged generation of grand fir. Canopy cover is also high, but these trees are not included in the overstory layer where a running crown fire would occur. Site 126 has relatively low density and canopy cover. Both of these sites are simulated to have crown indices reaching over 40 km/hr.

Mixed-conifer sites are simulated to have slightly lower crowning indices, suggesting drier conditions and more continuous canopy structure. Sites 105, 128, and 134 have lower tree density, but larger mature trees, suggesting larger crowns. Site 154 is simulated to have 14.3 km/hr crowning index at every increment throughout the simulation. This site has very high tree density and seems to be relatively even-aged with slightly lower canopy coverage, suggesting that the crown fire potential remains stable as the stand matures evenly.

The ponderosa pine sites depend mostly on tree density and age structure for crowning index levels (Reinhardt and Crookston 2003; Schmidt, Taylor, and Skinner 2008). Sites 119, 121, 122, and 135 are projected to have an unchanging crowning index of 14.3 km/hr throughout the century-long simulation. Site 129 increases throughout the next century as the few ponderosa pine trees present mature and the crowns grow larger.

The extremely sparse structure of Site 153 fails to undergo much change over the next century, as the crowning index remains mostly stable at approximately 30 km/hr.

Understanding the past trajectory of land cover and future fire type potential can help make inferences about the future trajectory of land cover class. For example, Table 10 shows the past land cover change in addition to future fire type for every study site. Site 153, a ponderosa pine site, progresses from passive crown fire to active crown fire in just one decade, then back to passive crown fire by 2087. This site could experience progression to a mixed-conifer or even grand fir site before it experiences mass density-related mortality near the end of the simulation. Site 105, which has been a mixed-conifer site since 1984, is simulated to experience conditional crown fire until approximately 2077. At this time the fire hazard intensifies to active crown fire, likely because the stand composition and density has shifted to support this fire type. Site 126 differs in that it was a mixed-conifer site in 1984, then progressed to a grand fir site by 2000 and remained so until 2017. This site is simulated to experience active crown fire until about 2067, where fire type reverts back to passive crown fire, likely due to density-based mortality.

Table 10 Land cover class change and future potential fire type for each study site through time.

	Land cover class change				Future potential fire type										
Site	1984	2000	2013	2017	2017	2027	2037	2047	2057	2067	2077	2087	2097	2107	2117
103	MC	RI	RI	RI	C	C	C	C	A	A	A	A	A	A	A
105	MC	MC	MC	MC	C	C	C	C	C	C	A	A	A	A	A
115	GF	MC	GF	GF	A	A	A	A	A	A	A	A	A	A	P
119	MC	PIPO	PIPO	PIPO	A	A	A	A	A	A	A	A	A	A	C
121	MC	MC	PIPO	PIPO	C	A	A	A	A	A	A	A	A	A	A
122	PIPO	MC	PIPO	PIPO	A	A	A	A	A	A	A	A	A	C	C
124	RI	RI	RI	RI	S	S	S	P	P	P	P	P	P	P	P
126	MC	GF	GF	GF	A	A	A	A	A	P	P	P	P	P	P
128	MC	MC	MC	MC	C	C	C	C	C	C	C	C	C	A	A
129	MC	PIPO	PIPO	PIPO	A	A	A	A	S	P	P	P	P	P	P
134	PIPO	MC	MC	MC	C	C	C	C	C	C	C	C	C	C	C
135	MC	MC	PIPO	PIPO	C	A	C	C	C	C	C	C	C	C	C
138	GF	GF	GF	GF	C	A	A	A	A	A	A	A	A	A	A
153	PIPO	PIPO	PIPO	PIPO	P	A	A	A	C	A	A	P	P	P	P
154	MC	MC	PIPO	MC	C	A	A	A	A	C	C	C	C	C	C
161	MC	MC	PIPO	GF	C	A	A	A	A	A	A	C	C	C	C
162	GF	GF	GF	GF	C	C	C	C	C	C	C	C	C	C	C

CHAPTER VII: CONCLUSIONS

It was found in this research that throughout the TCF, a continuous transition from more open ponderosa pine and mixed-conifer forest to uncharacteristically overstocked grand fir-dominated forest has drastically increased the potential for extreme fire behavior. These changes are due primarily to modern land use changes, including fire suppression, harvesting of large-diameter, fire resilient trees, grazing of fine fuels, and building of roads, which have allowed the over-accumulation of hazardous fuels capable of supporting high-intensity wildfire. When fire does occur in the TCF, high rates of tree mortality and economic repercussions can be expected. However, restoring the forest structure and composition to more closely emulate historic conditions will decrease wildfire severity potential and increase forest resilience to wildfire.

Study Limitations

This research is primarily limited by the amount fieldwork data collected. Resource limitations prevented a more representative amount of data to be collected and these stand types were classified somewhat broadly. A more robust study, involving more field data, would yield more specific results. It is also important to remember that the fire hazard map created in this research does not reflect the possible movement of fire through the forest based on the connectivity of different land cover types. Many other factors must be considered in the case of fire behavior, including the network of potential fire breaks (e.g. rivers, streams, roads, exposed bedrock), topography, wind direction, moisture availability, and others. Additionally, the FVS simulations were done without any management applied such as the timber harvesting and grazing that is ongoing in the TCF today, greatly simplifying the results. If all types of management being used currently in the TCF were applied in the simulation, the results may be quite different and, as with all simulations, should be used with caution.

Policy Implications

The results of this research highlight several concerns. Clearly, if no action is taken to mitigate hazardous fire risk, the TCF is at high risk for widespread mortality and damage to nearby structures. Decisions must be made by land managers regarding preventative versus reactive measures to control damage caused by wildfire or insect spread by reducing fuel loads and encouraging the transition from a grand fir-dominated landscape to one more alike historic conditions.

Because there is private property within the bounds of the TCF, care must be taken to reduce the potential for economic damage to the local homeowners in addition to the federal government if fire suppression becomes necessary, and to outline protocol for evacuation when wildfire does occur. A “let it burn” strategy would not be advisable in the TCF in the near future, and would likely cause tremendous irreversible damage to both private property and to the forest, possibly exceeding the potential cost of restoration efforts. Some degree of fire suppression may be required until the forest structure can be restored to conditions that support low- to moderate-severity fire behavior. As forest restoration is being implemented, management strategies should be reevaluated and adjusted often to best fit the needs of private landowners and TCF stakeholders.

Management Recommendations

To understand how land use change has changed the landscape of the TCF, the results of the air photo interpretation and remote sensing analysis were compared to the historic vegetation and fire regime records (Wright and Agee 2004) to characterize how disturbance regimes have been historically altered. The FVS results helped determine which stands in the Teanaway are in greatest need of restoration. Based on these results, most of the TCF is vulnerable to either conditional or active crown fire, inciting the need to begin forest restoration activities while planning for high-severity wildfire events. In the occurrence of high-severity wildfire, land managers will have to make decisions regarding the extent of suppression efforts.

Since the inception of this thesis, The Kittitas County Community Wildfire Protection Plan was introduced. The plan outlines changes that have occurred in the forest, which are discussed in this research, and ways for various stakeholders and landowners to reduce the potential for extreme fire behavior in the forest as well as developing "fire-adapted communities" in the wildland urban interface surrounding the TCF ("Community Wildfire Protection Plan" 2018). Community resilience to fire in the WUI generally involves the reduction of hazardous fuels on private property and reducing structure ignitability potential by using only fire-resistant building materials, which many landowners currently do on an individual basis. As humans continue to expand into the WUI and the forest continues to progress into late seral-stage forest types at mid- to low-elevations, these methods will only become more important, especially if the TCF continues to be utilized as a multi-use resource.

Data Dissemination

Results from this research will be made available to the Department of Natural Resources and the Washington Department of Fish and Wildlife to aid in satisfying the sustainability criteria laid out in the TCF Forest Management Plan (DNR 2015). In addition, land managers may use the results of this research to further understand the effects of land use change on disturbance regimes in the eastern Cascades and to justify the need for fuel treatments that reduce the potential for severe fire behavior. This thesis research will be submitted to *Northwest Science* for publication.

Future Research

Future research should be directed at applying current and future management practices of the TCF to the FVS simulations and expanding fieldwork surveys to be more representative of the forest. Adjustments to these practices can then be made based on the future goals for the structure and composition in the TCF to reduce severe disturbance potential. Climate change is another factor that should be considered in future studies, as the frequency and duration of droughts cause additional stress on trees and increase potential fire risk (Mote et al. 2014). Depending on the speed and intensity under which climate change occurs, future management may have to be extremely proactive. A single management plan will not accomplish fire resilience, rather, research should be a continuous process as we enter unknown climatic conditions.

In addition to restoring the forest, some attempts could be made to predict the movement of wildfire throughout the forest based on ignition points in order to properly establish evacuation procedures for local property owners. There are other simulation programs capable of doing this, such as Wildfire Analyst, a program used to simulate wildfire behavior and spread. Lastly, finer resolution satellite imagery and additional descriptive spectral indices could be used to better understand the relationship between spectral signatures of the forest and severe wildfire potential. Other disturbances, such as insect spread, could also be explored in the TCF. The relationship between the spectral signal of the forest and defoliation could provide a simple way to locate insect infestations in remote and unexplored areas.

LITERATURE CITED

Agee, J., and C. Skinner. 2005. Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* 211(1-2): 83-96.

Agee, J. 1996. The influence of forest structure on fire behavior. *Proceedings of the 17th Annual Forest Vegetation Management Conference* 52–68.

Ager, A., N. Vaillant, and M. Finney. 2011. Integrating fire behavior models and geospatial analysis for wildland fire risk assessment and fuel management planning. *Journal of Combustion* 2011: 1-19.

Arkle, R, D. Pilliod, and J. Welty. 2012. Pattern and process of prescribed fires influence effectiveness at reducing wildfire severity in dry coniferous forests. *Forest Ecology and Management* 276: 174-184.

Bentz, B., J. Regniere, C. Fettig, E. Hansen, J. Hayes, J. Hicke, R. Kelsey, J. Negron, and S. Seybold. 2010. Climate Change and Bark Beetles of the Western United States and Canada: Direct and Indirect Effects. *Bioscience* 60 (8): 602–13.

U.S. Department of the Interior, Bureau of Land Management and Office of the Solicitor (editors). 2001. The Federal Land Policy and Management Act, as amended. U.S. Department of the Interior, Bureau of Land Management Office of Public Affairs, Washington, D.C.

Bureau of Land Management. 2019. About Livestock Grazing on Public Lands. https://www.blm.gov/programs/natural-resources/rangelands-and-grazing/livestock-grazing/about (accessed July 3, 2019).

Boyd, Robert. 1999. *Indians, Fire, and the Land*. Corvallis, Oregon. Oregon State University Press.

Buchanan, J. B. 2016. Periodic status review for the Northern Spotted Owl in Washington. Washington Department of Fish and Wildlife, Olympia, Washington.

Callister, K. E., P. A. Griffioen, S. C. Avitabile, A. Haslem, L. T. Kelly, S. A. Kenny, D. G. Nimmo, L. M. Farnsworth, R. S. Taylor, S. J. Watson, A. F. Bennett, M. F. Clark. 2016. Historical Maps from Modern Images: Using Remote Sensing to Model and Map Century-Long Vegetation Change in a Fire-Prone Region. *PLoS ONE* 11(3): 1-18.

Camp, A. E. 1999. Age Structure and Species Composition Changes Resulting from Altered Disturbance Regimes on the Eastern Slopes of the Cascades Range, Washington. *Journal of Sustainable Forestry* 9(3/4): 39-67.

Camp, A., C. Oliver, P. Hessburg, and R. Everett. 1997. Predicting Late-Successional Fire Refugia Pre-Dating European Settlement in the Wenatchee Mountains. *Forest Ecology and Management* 95: 63-77.

Churchill, D. J., A. J. Larson, M. C. Dahlgreen, J. F. Franklin, P. F. Hessburg, and J. A. Lutz. 2013. Restoring Forest Resilience: From Reference Spatial Patterns to Silvicultural Prescriptions and Monitoring. *Forest Ecology and Management* 291: 442-457.

Dixon, G. 2013. Essential FVS: A User's Guide. United States Department of Agriculture. Forest Management Service Center, Fort Collins, Colorado.

Department of Natural Resources. 2015. Teanaway Community Forest Management Plan. Olympia, Washington.

Everett, R. L., R. Schellhaas, D. Keenum, D. Spurbeck, and P. Ohlson. 2000. Fire History in the Ponderosa Pine/Douglas-Fir Forests on the East Slope of the Washington Cascades. *Forest Ecology and Management* 129: 207-225.

Fettig, C. J., K. D. Klepzig, R. F. Billings, A. S. Munson, T. E. Nebeker, J. F. Negrón, and J. T. Nowak. 2007. The Effectiveness of Vegetation Management Practices for Prevention and Control of Bark Beetle Infestations in Coniferous Forests of the Western and Southern United States. *Forest Ecology and Management* 238 (1–3): 24–53.

Fitzgerald, S. A. 2005. Fire Ecology of Ponderosa Pine and the Rebuilding of Fire-Resilient Ponderosa Pine Ecosystems. Gen. Tech. Rep PSW-GTR-198. United States Department of Agriculture, Albany, California.

Forman, R. T. T., and L. E Alexander. 1998. Roads and Their Major Ecological Effects. *Annual Review of Ecology and Systematics* 29: 207–31.

Franklin, J. F., and C.T. Dyrness. 1973. Natural Vegetation of Oregon and Washington. USDA Forest Service General Technical Report, Pacific Northwest Forest and Range Experiment Station PNW-8, 417.

Franklin, J. F., R. K. Hagmann, and L. S. Urgenson. 2014. Interactions between Societal Goals and Restoration of Dry Forest Landscapes in Western North America. *Landscape Ecology* 29: 1645-1655.

Fulé, P. Z., J. E. Crouse, J. P. Roccaforte, and E. L. Kalies. 2012. “Do thinning and/or burning treatments in western USA ponderosa or Jeffrey pine-dominated forests help restore natural fire behavior? *Forest Ecology and Management* 269: 68-81.

Glauert, E. T., and M. H. Kunz. 1976. Kittitas Frontiersmen. Ellensburg, Washington. Ellensburg Public Library.

Harrod, R. J., B. H. McRae, and W. E. Hartl. 1999. Historical Stand Reconstruction in Ponderosa Pine Forests to Guide Silvicultural Prescriptions. *Forest Ecology and Management* 114: 433-446.

Haugo, R. D., S. A. Hall, E. M. Gray, P. Gonzalez, and J. D. Bakker. 2010. Influences of Climate, Fire, Grazing, and Logging on Woody Species Composition along an Elevation Gradient in the Eastern Cascades, Washington. *Forest Ecology and Management* 260: 2204-2213.

Henderson, E. M. 1990. The Pine Tree Express, a History of the Cascade Lumber Company's Pine Hauling Railroad in Kittitas County, Washington 1916-1946. Lacey, Washington. E.M. Henderson.

Hessburg, P. F., and J. K. Agee. 2003. An Environmental Narrative of Inland Northwest United States Forests, 1800-2000. *Forest Ecology and Management* 178: 23-59.

Hessburg, P. F., D. J. Churchill, A. J. Larson, R. D. Haugo, C. Miller, T. A. Spies, M. P. North, N. A. Povak, R. T. Belote, P. H. Singleton, W. L. Gaines, R. E. Keane, G. H. Aplet, S. L. Stephens, P. Morgan, P. A. Bisson, B. E. Rieman, R. B. Salter, G. H. Reeves. 2015. Restoring Fire-Prone Inland Pacific Landscapes: Seven Core Principles. *Landscape Ecology* 30: 1805-1835.

Hessburg, P. F., T. A. Spies, D. A. Perry, C. N. Skinner, A. H. Taylor, P. M. Brown, S. L. Stephens, A. J. Larson, D. J. Churchill, N. A. Povak, P. H. Singleton, B. McComb, W. J. Zielinski, B. M. Collins, R. B. Salter, J. J. Keane, J. F. Franklin, G. Riegel. 2016. Tamm

Review: Management of Mixed-Severity Fire Regime Forests in Oregon, Washington, and Northern California. *Forest Ecology and Management* 366: 221-250.

Hessburg, P. F, B. G Smith, R B. Salter. 1999. Detecting Change in Forest Spatial Patterns from Reference Conditions. *Ecological Society of America* 9 (4): 1232–52.

Hood, S. M., S. Baker, and A. Sala. 2016. Fortifying the Forest: Thinning and Burning Increase Resistance to a Bark Beetle Outbreak and Promote Forest Resilience. *Ecological Applications* 9(4): 1232-1252.

Jensen, J. R. 2005. Introductory Digital Image Processing. Provo, Utah: Pearson.

Johnson, K. N. and F. J. Swanson. 2009. Historical Context of Old-Growth Forests in the Pacific Northwest - Policy, Practices, and Competing Worldviews. In: Spies, T. A., S. L. Duncan. Old growth in a new world: A Pacific Northwest icon reexamined. Washington, DC: Covelo, CA: Island Press: 12-28. Chapter 2.

Kao, H., H. Ren, and C. Lee. 2014. Calibrated Ratio Approach for Vegetation Detection in Shaded Areas. *Journal of Applied Remote Sensing* 8 (1): 083543.

Keyser, C. E., and G. E. Dixon. 2013. East Cascades (EC) Variant Overview. United States Department of Agriculture. Forest Management Service Center, Fort Collins, Colorado.

Kittitas County Conservation District. 2018. “Community Wildfire Protection Plan.” Ellensburg, Washington.

Larson, A. J., and D. Churchill. 2012. Tree Spatial Patterns in Fire-Frequent Forests of Western North America, Including Mechanisms of Pattern Formation and Implications for Designing Fuel Reduction and Restoration Treatments. *Forest Ecology and Management* 267: 74-92.

Lillybridge, T. R., B. L. Kovalchik, C. K. Williams, and B. G. Smith. 1995. Field Guide for Forested Plant Association of the Wenatchee National Forest. General Technical Report PNW-GTR-359 44 (4): 335.

Mattson, W. J., and R. A. Haack. 1987. The Role of Drought in Outbreaks of Plant-Eating Insects. *BioScience* 37 (2): 110–18.

Meigs, G. W., R. E. Kennedy, and W. B. Cohen. 2011. A Landsat Time Series Approach to Characterize Bark Beetle and Defoliator Impacts on Tree Mortality and Surface Fuels in Conifer Forests. *Remote Sensing of Environment* 115 (12): 3707–18.

Morgan, J. L., S. E. Gergel, and N. C. Coops. 2010. Aerial Photography: A Rapidly Evolving Tool for Ecological Management. *BioScience* 60 (1): 47–59.

Morgan, J. L., and S. E. Gergel. 2010. Quantifying Historic Landscape Heterogeneity from Aerial Photographs Using Object-Based Analysis. *Landscape Ecology* 985–98.

Mote, P. A., A. K. Snover, S. Capalbo, S.D. Eigenbrode, P. Glick, J. Littell, R. Raymondi, and S. Reeder. 2014. Ch. 21: Northwest. *Climate Change Impacts in the United States: The Third National Climate Assessment*, 487-513.

Plummer, F. G. 1902. Forest Conditions in the Cascade Range, Washington between the Washington and Mount Rainier Forest Reserves. USGS.

Pyne, S. J. 1982. Fire in America. Seattle, Washington. University of Washington Press.

Reinhardt, E. and N. L. Crookston. 2003. Fire and Fuels Extension to the Forest Vegetation Simulator. General Technical Report - Rocky Mountain Research Station, USDA Forest Service, RMRS-GTR-116: 209-pp.

Ripley, T., G. Scrimgeour, and M. S. Boyce. 2005. Bull Trout (Salvelinus Confluentus) Occurrence and Abundance Influenced by Cumulative Industrial Developments in a Canadian Boreal Forest Watershed. *Forest Ecology and Management* 2442: 2431–2442.

Rorig, M. L., and S. A. Ferguson. 2002. Characteristics of Lightning and Wildland Fire Ignition in the Pacific Northwest. *Journal of Applied Meteorology* 38 (11): 1565–75.

Roy, D. P., M. A. Wulder, T. R. Loveland, C. E. Woodcock, R. G. Allen, M. C. Anderson, D. Helder, J.R. Irons, D.M. Johnson, R. Kennedy, T.A. Scambos, C.B. Schaaf, J.R. Schott, Y. Sheng, E.F. Vermote, A.S. Belward, R. Bindschadler, W.B. Cohen, Z. Zhu. 2014. Landsat-8: Science and Product Vision for Terrestrial Global Change Research. *Remote Sensing of Environment* 145: 154–72.

Sandisen, D. and W. Christiansen. 2012. Yakima River Basin Integrated Water Resource Management Plan Final Programmatic Environmental Impact Statement. 12-12-002. United States Department of the Interior and Washington State Department of Ecology, Yakima, Washington.

Schmidt, D. A., A. H. Taylor, and C. N. Skinner. 2008. The Influence of Fuels Treatment and Landscape Arrangement on Simulated Fire Behavior, Southern Cascade Range, California. *Forest Ecology and Management* 255: 3170–3184.

Stephens, S. L., J. K. Agee, P. Z. Fulé, M. P. North, W. H. Romme, T. W. Swetnam, and M. G. Turner. 2013. Managing Forests and Fire in Changing Climates. *Science* 342 (6154): 41–42.

Stephens, S. L., J. D. McIver, R. E. J. Boerner, C. J. Fettig, J. B. Fontaine, B. R. Hartsough, P. L. Kennedy, and D. W. Schwilk. 2012. The Effects of Forest Fuel-Reduction Treatments in the United States. *Bioscience* 62 (6): 549–60.

Stine, P., P. Hessburg, T. Spies, M. Kramer, C. J. Fettig, A. Hansen, J. Lehmkuhl, K. O'Hara, K. Polivka, P. Singleton, S. Charnley, A. Merschel, R. White. 2014. The Ecology and Management of Moist Mixed-Conifer Forests in Eastern Oregon and Washington: A Synthesis of the Relevant Biophysical Science and Implications for Future Land Management. PNW-GTR-897 United States Department of Agriculture, Portland, Oregon.

Symons, J.N., D.H.K. Fairbanks, and C.N. Skinner. 2008. Influences of Stand Structure and Fuel Treatments on Wildfire Severity at Blacks Mountain Experimental Forest, Northeastern California. *The California Geographer* 48: 61–82.

Taylor, A. H., and A. Guarı. 2005. Drought Triggered Tree Mortality in Mixed Conifer Forests in Yosemite National Park, California, USA. *Forest Ecology and Management* 218: 229–44.

Thomas, J. W., J. F. Franklin, J. Gordon, and K. N. Johnson. 2006. The Northwest Forest Plan: Origins, Components, Implementation Experience, and Suggestions for Change. *Conservation Biology* 20(2): 277-287.

USDA. 2010. Soil Survey of Kittitas County Area, Washington. United States Department of Agriculture, Kittitas County, Washington.

USGS. 2014. Hydrogeologic Framework and Groundwater / Surface-Water Interactions of the Upper Yakima River Basin, Kittitas County, Central Washington. Scientific Investigations Report 2014-5119. United States Geological Survey, Reston, Virginia.

USGS. 2015. Landsat Surface Reflectance Data. USGS Eros 6932 (April): 20153034.

Walsh, M. K., H. J. Duke, and K. C. Haydon. 2018. Toward a Better Understanding of Climate and Human Impacts on Late Holocene Fire Regimes in the Pacific Northwest, USA. *Progress in Physical Geography* 42 (4): 478–512.

Westerling, A.L., H.G. Hidalgo, D.R. Cayan, T.W. Swetnam. 2019. Warming and Earlier Spring Increase Western U. S. Forest Wildfire Activity. *Science* 313 (5789): 940–43.

Williams, G. W. 2005. The USDA Forest Service: The First Century. USDA Forest Service, Washington, D.C.

Wimberly, M. C. and Z. Liu. 2014. Interactions of Climate, Fire, and Management in Future Forests of the Pacific Northwest. *Forest Ecology and Management* 327: 270-279.

WRCC. 2017. Cle Elum, WA. Western Regional Climate Center. https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?wa1504 (accessed June 4, 2019).

Wright, C. S., and J. K. Agee. 2004. Fire and vegetation history in the eastern Cascade mountains, Washington. *Ecological Applications* 14(2): 443-459.

Young, N. E., R. S. Anderson, S. M. Chignell, A. G. Vorster, R. Lawrence, and P. H. Evangelista. 2017. A Survival Guide to Landsat Preprocessing. *Ecology* 98 (4): 920–32.

Youngblood, A., C. S. Wright, R. D. Ottmar, and J. D. McIver. 2008. Changes in Fuelbed Characteristics and Resulting Fire Potentials after Fuel Reduction Treatments in Dry Forests of the Blue Mountains, Northeastern Oregon. *Forest Ecology and Management* 255: 3151-3169.

APPENDIX A. Individual tree data from all study sites.

PP: ponderosa pine; DF: Douglas-fir; GF: grand fir; WH: western hemlock; SW: scouler willow; LP: lodgepole pine; A: aspen; WL: western larch; RA: red alder; BH: black hawthorn; MH: mountain hemlock

Site #	Species	% Live Crown	Tree Height (m)	Height to Ladder Fuels (m)	DBH (cm)
103	PP	80	2.13	0.61	2.54
103	PP	60	3.35	0.61	5.08
103	PP	80	5.03	0.76	7.62
103	PP	60	6.86	0.30	20.32
103	DF	80	3.96	0.15	3.81
103	PP	60	2.44	0.15	1.27
103	DF	30	21.34	0.30	12.70
103	GF	50	3.66	0.30	1.27
103	WH	70	3.35	0.46	5.08
103	GF	90	3.20	0.15	7.62
103	WH	80	5.49	0.15	15.24
103	WH	80	4.88	0.15	7.62
103	GF	95	5.03	0.00	10.16
103	DF	95	3.96	0.15	6.35
103	DF	70	16.31	2.44	38.10
103	DF	65	15.39	2.59	33.02
103	PP	30	17.37	3.81	38.10
103	PP	50	3.66	0.76	10.16
103	DF	100	1.83	0.00	1.27
105	DF	90	17.22	2.44	29.21
105	DF	80	15.24	1.98	27.94
105	PP	90	2.90	0.15	3.81
105	SW	95	3.66	0.00	1.27
105	GF	100	1.83	0.00	1.27
105	PP	80	3.35	0.15	2.54
105	SW	95	3.96	0.00	1.27
105	PP	90	3.05	0.91	3.81
105	PP	90	3.05	0.61	2.54
105	PP	20	22.71	13.11	35.56
105	SW	95	4.88	0.00	1.27
105	PP	80	6.10	0.30	8.89
105	PP	80	3.96	0.91	3.81
105	DF	70	16.31	3.20	30.48
105	DF	80	11.58	1.52	17.78
105	PP	0	4.27	0.00	22.86
105	GF	90	2.74	0.00	1.27
105	DF	0	10.52	0.00	20.32
105	GF	85	4.88	0.15	7.62

105	PP	40	19.66	9.60	40.64
115	GF	90	1.52	0.30	1.27
115	GF	15	2.44	0.30	2.54
115	GF	10	3.66	0.30	2.54
115	GF	40	3.05	0.91	2.54
115	GF	30	5.49	0.61	5.08
115	GF	50	4.57	1.22	5.08
115	GF	20	3.05	0.30	2.54
115	LP	65	15.24	0.61	15.24
115	GF	80	5.49	0.91	3.81
115	GF	40	1.83	1.22	1.27
115	GF	30	2.44	0.91	1.27
115	GF	30	2.74	0.91	2.54
115	GF	20	1.83	0.30	1.27
115	GF	60	6.71	0.91	5.08
115	GF	70	8.23	0.61	7.62
115	GF	75	10.67	0.91	7.62
115	GF	80	13.72	1.07	13.97
115	GF	30	3.66	0.30	2.54
115	GF	30	1.83	0.15	1.27
115	A	15	11.28	1.83	1.27
115	GF	80	3.05	0.91	2.54
115	GF	100	1.68	0.30	1.27
115	GF	100	1.83	0.30	1.27
115	GF	100	1.22	0.30	1.27
115	GF	100	1.68	0.30	1.27
115	GF	100	1.68	0.30	1.27
115	GF	100	1.83	0.30	1.27
115	GF	100	2.13	0.30	1.27
115	GF	100	1.83	0.30	1.27
115	GF	100	1.52	0.30	1.27
115	GF	100	1.52	0.15	1.27
115	GF	100	1.83	0.30	1.27
115	GF	100	2.13	0.30	1.27
115	GF	100	1.22	0.30	1.27
115	GF	15	2.74	0.23	1.27
115	GF	100	1.22	0.30	1.27
115	GF	100	1.52	0.30	1.27
115	GF	100	1.83	0.30	1.27
115	DF	100	1.52	0.30	1.27
115	GF	100	1.83	0.30	1.27
115	GF	40	2.59	0.15	2.54
115	GF	25	2.13	1.52	1.27

115	GF	15	2.44	0.30	1.27
115	GF	40	21.95	0.30	44.45
115	GF	70	2.13	0.30	2.54
119	PP	80	4.88	0.91	15.24
119	PP	60	3.05	0.15	5.08
119	PP	50	2.74	0.15	1.27
119	PP	50	3.20	0.30	5.08
119	PP	30	2.13	0.61	1.27
119	PP	60	3.05	0.91	3.81
119	PP	70	4.72	0.15	1.27
119	PP	10	2.13	0.91	2.54
119	PP	70	3.35	1.22	2.54
119	PP	30	2.74	1.22	1.27
119	PP	40	4.42	1.83	3.81
119	PP	60	5.18	1.52	10.16
119	PP	50	4.88	1.83	7.62
119	PP	40	4.27	1.52	3.81
119	PP	30	3.35	0.91	1.27
119	PP	40	3.96	1.22	2.54
119	PP	10	1.83	0.61	1.27
119	PP	60	4.57	1.22	5.08
119	PP	30	3.96	1.22	2.54
119	PP	0	2.44	0.15	2.54
119	PP	30	4.88	0.91	7.62
119	PP	0	3.66	0.91	2.54
119	PP	20	4.39	1.52	2.54
119	PP	20	2.44	0.91	1.27
119	PP	30	2.74	0.61	2.54
119	PP	20	1.52	0.15	1.27
119	PP	30	1.52	0.15	2.54
119	PP	30	1.22	0.15	1.27
119	PP	20	5.94	1.83	10.16
119	PP	70	7.32	1.22	15.24
119	PP	60	5.79	1.22	12.70
119	PP	30	5.49	0.91	2.54
119	PP	40	7.77	0.91	17.78
119	PP	50	5.79	1.22	12.70
119	PP	30	7.92	1.83	15.24
119	PP	15	5.03	1.83	1.27
119	PP	20	5.49	1.52	2.54
119	PP	60	7.32	0.91	20.32
119	PP	20	6.40	2.13	3.81
119	PP	20	6.10	1.22	5.08

119	PP	50	5.18	0.91	7.62
119	DF	90	7.01	0.15	15.24
119	PP	20	2.44	0.61	1.27
119	PP	70	4.11	0.91	5.08
119	PP	60	4.27	0.91	7.62
119	PP	30	3.35	0.61	3.81
119	PP	60	2.74	0.61	10.16
119	GF	90	5.18	0.15	15.24
119	PP	10	4.27	2.44	1.27
119	DF	90	5.79	0.15	10.16
119	DF	90	4.88	0.15	2.54
119	DF	90	3.96	0.15	2.54
119	PP	40	2.13	1.22	1.27
119	PP	30	1.52	0.15	1.27
119	PP	60	3.35	0.61	5.08
119	PP	40	5.49	0.61	7.62
119	DF	90	4.27	0.15	3.81
119	PP	40	2.74	0.30	1.27
119	PP	80	8.08	0.91	24.13
119	PP	50	2.13	0.30	1.27
119	PP	30	1.52	0.15	1.27
119	PP	20	1.22	0.15	1.27
119	PP	60	1.83	0.00	1.27
119	PP	60	1.52	0.00	1.27
119	PP	80	18.44	2.74	43.18
119	PP	70	18.75	4.27	48.26
119	DF	90	2.44	0.15	1.27
121	PP	10	9.75	1.83	15.24
121	PP	10	9.14	1.52	19.05
121	PP	20	7.77	0.61	7.62
121	PP	30	8.23	1.22	20.32
121	DF	80	6.55	0.61	8.89
121	DF	70	3.66	0.46	2.54
121	PP	15	7.01	3.66	6.35
121	PP	15	6.55	3.05	6.35
121	PP	20	10.06	1.83	19.05
121	PP	30	9.30	1.83	17.78
121	PP	30	5.49	1.37	7.62
121	PP	30	8.53	1.07	13.97
121	PP	20	8.08	1.22	12.70
121	PP	10	5.79	1.22	2.54
121	PP	10	7.47	1.83	5.08
121	DF	70	3.66	0.46	1.27

121	DF	60	2.74	0.15	1.27
121	GF	80	4.11	0.15	5.08
121	DF	90	22.71	1.07	45.72
121	PP	30	8.23	1.83	17.78
121	PP	20	5.64	1.07	6.35
121	PP	5	1.83	1.22	1.27
121	PP	20	8.08	0.91	12.70
121	PP	25	7.77	2.13	13.97
121	PP	10	3.96	1.83	2.54
121	PP	40	9.45	1.83	22.86
121	PP	25	7.32	0.91	11.43
121	PP	20	6.55	0.76	8.89
121	PP	20	5.64	0.91	7.62
121	PP	15	2.90	1.22	2.54
121	PP	20	3.35	1.22	2.54
121	PP	5	4.88	1.52	2.54
121	PP	70	8.53	0.46	39.37
121	PP	60	8.08	1.52	16.51
121	PP	15	7.16	0.91	6.35
121	DF	80	7.92	0.61	22.86
121	PP	30	5.49	0.91	5.08
121	PP	50	7.92	1.52	12.70
121	PP	5	2.13	0.46	1.27
121	PP	30	2.44	0.30	3.81
121	DF	80	1.83	0.15	1.27
121	PP	40	3.35	0.30	1.27
121	PP	30	5.79	0.91	7.62
121	PP	30	7.47	1.52	15.24
121	PP	30	5.64	1.52	5.08
121	PP	30	6.10	2.44	12.70
121	PP	30	5.79	1.07	12.70
121	PP	5	2.13	0.91	1.27
121	PP	60	6.55	2.13	5.08
121	PP	60	6.10	1.52	11.43
121	PP	10	4.57	2.13	2.54
121	GF	60	3.66	0.15	2.54
121	PP	30	6.10	1.22	8.89
121	PP	70	7.92	1.83	33.02
121	PP	50	8.99	1.22	17.78
121	PP	20	3.66	1.22	1.27
121	PP	20	3.05	1.52	1.27
121	PP	50	7.01	1.37	22.86
121	PP	20	2.13	0.76	1.27

121	DF	85	10.52	0.46	19.05
121	PP	15	2.44	1.22	1.27
121	PP	15	2.44	1.07	1.27
121	PP	70	8.53	1.22	20.32
121	PP	10	6.55	1.37	2.54
121	PP	30	7.77	1.22	7.62
121	PP	50	8.23	1.07	12.70
121	DF	30	7.32	0.61	13.97
121	DF	50	8.23	1.52	15.24
121	PP	30	5.79	1.83	10.16
121	PP	30	8.69	1.52	20.32
121	PP	30	9.14	1.07	13.97
121	GF	80	1.83	0.15	1.27
121	PP	20	2.90	1.22	1.27
121	PP	5	2.44	1.83	1.27
121	PP	5	1.83	1.52	1.27
121	PP	20	7.16	1.22	12.70
121	PP	40	6.10	1.37	15.24
121	PP	20	5.03	0.91	2.54
121	PP	40	9.60	2.13	22.86
121	PP	35	10.97	0.91	31.75
121	PP	30	7.01	0.91	15.24
121	PP	40	7.62	1.22	19.05
121	PP	40	6.55	1.22	10.16
121	PP	15	3.35	1.83	2.54
121	PP	40	7.47	0.30	19.05
121	PP	70	4.57	0.15	10.16
121	PP	20	5.03	0.61	2.54
121	PP	20	4.27	0.91	2.54
121	PP	10	5.49	0.91	7.62
121	PP	30	7.92	1.52	12.70
121	PP	30	7.01	1.83	17.78
121	PP	30	6.10	0.91	7.62
121	PP	5	5.18	0.91	2.54
121	PP	20	8.53	1.83	15.24
121	PP	30	9.30	1.52	19.05
121	PP	30	9.14	0.76	22.86
121	PP	15	5.49	0.91	7.62
121	PP	5	2.74	1.83	1.27
121	PP	5	3.05	1.83	1.27
121	PP	5	2.74	2.13	1.27
121	DF	90	1.83	0.15	1.27
121	PP	70	4.11	0.91	3.81

121	PP	70	5.49	1.68	10.16
121	PP	50	1.52	0.46	1.27
121	PP	40	1.83	0.61	1.27
122	PP	90	5.64	1.83	15.24
122	PP	70	5.18	1.52	12.70
122	PP	80	4.27	0.91	12.70
122	PP	70	4.42	0.91	11.43
122	PP	80	4.27	1.22	15.24
122	PP	70	2.74	1.22	2.54
122	PP	70	1.83	0.61	1.27
122	PP	80	4.57	1.22	7.62
122	PP	80	2.74	0.46	2.54
122	PP	90	5.49	1.52	7.62
122	PP	90	6.10	1.52	17.78
122	PP	70	4.57	1.22	5.08
122	PP	70	5.64	2.44	12.70
122	PP	50	4.11	1.22	5.08
122	PP	80	5.79	1.22	12.70
122	PP	70	4.88	1.52	10.16
122	PP	80	6.40	1.22	15.24
122	PP	70	5.49	0.91	15.24
122	PP	80	7.92	1.52	22.86
122	PP	70	7.32	1.22	15.24
122	PP	80	6.10	1.83	12.70
122	PP	80	6.10	0.61	20.32
122	PP	80	5.79	1.22	12.70
122	PP	70	5.18	1.52	10.16
122	PP	50	3.35	0.30	2.54
122	PP	90	4.88	0.91	15.24
122	PP	70	7.32	0.61	20.32
122	PP	70	4.72	1.22	17.78
122	PP	80	3.96	0.61	15.24
122	PP	80	3.66	0.30	5.08
122	PP	80	4.27	0.91	15.24
122	PP	60	2.44	0.61	1.27
122	PP	70	8.23	1.22	20.32
122	PP	60	7.32	0.91	15.24
122	PP	70	4.57	0.61	12.70
122	PP	80	5.64	0.91	15.24
122	GF	90	9.60	0.30	33.02
122	PP	50	4.27	1.52	3.81
122	PP	60	2.44	0.91	1.27
122	PP	50	1.22	0.30	1.27

122	PP	50	4.88	0.91	5.08
122	PP	70	5.33	0.91	7.62
122	PP	70	3.96	0.61	7.62
122	PP	70	4.27	0.91	7.62
122	PP	80	4.57	0.61	7.62
122	PP	80	6.40	0.61	15.24
122	PP	40	20.88	5.18	63.50
122	PP	85	4.27	0.61	12.70
122	PP	80	6.55	0.91	20.32
122	PP	80	5.79	0.61	20.32
122	PP	80	1.83	0.15	1.27
122	GF	60	3.96	0.15	7.62
124	DF	90	4.27	0.30	2.54
124	WL	90	26.06	3.05	55.88
124	PP	60	15.09	0.30	21.59
124	RA	20	5.79	0.30	1.27
124	GF	80	1.83	0.15	1.27
124	GF	90	2.13	0.15	1.27
124	GF	90	3.66	0.15	2.54
124	GF	90	3.51	0.15	2.54
124	WL	40	28.50	14.17	35.56
124	GF	90	3.66	0.30	8.89
124	WL	80	25.30	2.74	50.80
124	BH	90	5.49	1.07	2.54
124	DF	85	17.37	1.83	43.18
124	DF	80	2.74	0.15	2.54
124	DF	90	13.56	3.66	27.94
124	GF	90	3.96	0.15	3.81
126	DF	90	4.88	0.30	2.54
126	DF	90	4.27	0.30	2.54
126	DF	90	5.18	0.30	2.54
126	GF	90	2.13	0.30	2.54
126	DF	90	4.72	0.30	2.54
126	PP	20	4.88	0.91	2.54
126	GF	90	4.88	0.46	5.08
126	GF	90	1.52	0.15	1.27
126	GF	90	1.52	0.15	1.27
126	GF	90	1.83	0.15	2.54
126	GF	90	2.44	0.15	2.54
126	GF	90	5.49	0.30	10.16
126	GF	90	5.64	0.15	10.16
126	GF	90	3.66	0.15	7.62
126	MH	80	3.51	0.61	8.89

126	DF	90	1.22	0.00	1.27
126	GF	90	3.05	0.15	2.54
126	GF	90	1.83	0.15	1.27
126	PP	85	7.77	0.46	17.78
126	PP	70	0.91	0.15	1.27
126	PP	90	2.74	0.46	10.16
126	PP	90	2.44	0.46	1.27
126	GF	90	2.13	0.15	1.27
126	GF	90	1.52	0.15	1.27
126	PP	70	5.79	0.46	12.70
126	DF	95	5.18	0.15	8.89
126	DF	95	4.88	0.15	10.16
126	DF	90	1.68	0.15	1.27
126	GF	90	5.18	0.15	2.54
126	GF	90	4.27	0.15	1.27
126	GF	90	1.83	0.15	1.27
126	PP	80	3.66	0.46	2.54
126	DF	100	5.79	0.91	5.08
126	GF	100	2.29	0.15	1.27
126	PP	80	2.29	0.91	2.54
126	GF	100	1.52	0.15	1.27
126	PP	70	5.49	0.91	8.89
126	GF	100	1.83	0.15	1.27
126	PP	90	1.83	0.30	2.54
126	GF	90	5.18	0.15	5.08
126	PP	75	3.66	0.46	2.54
128	GF	80	2.13	0.15	2.54
128	GF	90	1.68	0.15	1.27
128	PP	75	3.81	0.46	7.62
128	PP	65	3.66	0.76	10.16
128	GF	90	2.44	0.30	1.27
128	GF	80	13.11	0.91	31.75
128	DF	70	6.55	0.61	17.78
128	GF	70	3.35	1.22	7.62
128	DF	60	5.18	2.44	10.16
128	DF	40	2.44	1.83	2.54
128	DF	50	3.96	2.13	3.81
128	DF	15	3.05	3.66	2.54
128	DF	30	1.83	0.91	1.27
128	DF	30	4.27	3.05	2.54
128	DF	90	1.52	0.15	1.27
128	GF	20	3.96	0.91	2.54
128	PP	60	3.66	0.46	5.08

128	PP	50	2.13	0.46	2.54
128	GF	30	17.68	11.58	33.02
128	DF	20	14.02	6.71	24.13
128	DF	70	9.91	3.96	17.78
128	GF	80	3.66	0.30	2.54
128	DF	70	8.38	3.05	25.40
128	GF	40	15.70	5.64	33.02
128	GF	90	1.83	0.15	1.27
128	GF	80	2.44	0.15	2.54
129	LP	95	3.51	0.15	15.24
129	PP	70	4.42	0.30	10.16
129	GF	80	1.98	0.15	2.54
129	GF	70	1.83	0.15	2.54
129	PP	90	5.33	0.15	24.13
129	LP	85	4.42	0.15	22.86
129	PP	70	3.35	0.30	3.81
129	PP	70	3.51	0.30	3.81
129	PP	85	6.86	0.46	30.48
129	PP	70	3.05	0.30	12.70
129	PP	80	5.79	0.30	15.24
129	LP	90	6.40	0.15	17.78
134	PP	25	12.19	8.38	21.59
134	DF	80	29.41	0.91	68.58
134	PP	40	25.45	7.01	54.61
134	PP	30	16.00	2.74	22.86
134	PP	55	28.65	12.19	54.61
134	DF	30	6.86	3.66	13.97
134	DF	50	21.79	1.22	50.80
134	GF	20	5.33	2.44	2.54
134	GF	30	6.25	2.13	5.08
134	DF	35	11.43	4.27	17.78
134	PP	35	26.52	4.72	48.26
134	GF	40	10.21	3.05	21.59
134	GF	30	13.87	4.27	21.59
134	DF	30	14.02	11.58	19.05
134	DF	40	11.58	1.22	17.78
134	GF	60	1.83	0.00	1.27
134	GF	40	2.44	0.46	5.08
134	DF	40	24.84	8.38	66.04
134	PP	20	25.76	13.56	44.45
134	DF	60	6.10	1.22	10.16
134	PP	20	5.18	3.05	11.43
134	DF	60	3.66	0.91	7.62

135	PP	80	5.18	1.22	7.62
135	DF	80	17.98	4.27	41.91
135	GF	70	8.23	1.52	25.40
135	GF	90	3.05	0.61	7.62
135	GF	70	7.01	0.91	15.24
135	GF	70	8.99	1.22	26.67
135	GF	50	5.49	1.83	20.32
135	GF	70	16.46	1.52	36.83
135	DF	80	4.57	0.15	5.08
135	GF	70	3.66	0.15	10.16
135	GF	70	4.57	0.91	12.70
135	GF	30	3.05	1.52	7.62
135	GF	75	8.69	1.83	22.86
135	GF	80	21.79	4.42	50.80
135	PP	80	1.83	0.61	2.54
135	PP	90	2.13	0.15	1.27
135	GF	90	14.02	0.61	38.10
135	GF	90	12.19	1.52	34.29
135	PP	80	5.49	0.30	7.62
138	PP	70	14.33	0.61	35.56
138	PP	75	14.02	1.83	30.48
138	PP	55	12.65	1.98	17.78
138	PP	60	11.13	1.52	29.21
138	PP	50	12.50	1.22	30.48
138	GF	90	1.68	0.15	1.27
138	GF	80	1.68	0.30	1.27
138	GF	80	1.52	0.15	1.27
138	PP	30	11.43	1.83	27.94
138	PP	40	12.80	1.22	20.32
138	GF	75	17.07	1.83	27.94
138	GF	70	9.75	2.44	12.70
138	GF	50	13.56	2.29	15.24
138	GF	50	8.38	2.74	12.70
138	PP	12.5	9.14	1.22	3.81
138	GF	60	9.75	2.44	12.70
138	GF	30	3.66	2.13	3.81
138	GF	10	2.44	0.91	2.54
138	GF	60	8.23	1.52	8.89
138	GF	10	5.49	1.07	10.16
138	GF	70	10.21	2.44	19.05
138	GF	60	8.53	0.91	7.62
138	GF	10	2.74	0.76	7.62
138	GF	70	19.51	1.83	19.05

138	GF	60	15.85	0.91	17.78
138	GF	75	8.84	1.83	15.24
138	GF	60	2.44	1.22	3.81
138	GF	15	2.13	0.91	1.27
138	GF	80	17.98	1.52	35.56
138	GF	70	18.29	2.44	31.75
138	GF	70	13.41	3.81	20.32
138	GF	50	11.89	1.68	17.78
138	GF	40	14.63	2.59	24.13
138	GF	15	2.74	1.22	3.81
138	GF	80	5.79	0.91	12.70
138	GF	15	2.90	0.46	1.27
153	PP	50	3.96	0.15	7.62
153	PP	60	4.42	0.15	10.16
153	PP	80	7.16	0.61	17.78
153	PP	65	5.33	0.61	10.16
154	DF	90	2.13	0.15	1.27
154	PP	60	1.83	0.15	1.27
154	PP	60	4.27	0.00	5.08
154	DF	90	2.29	0.15	2.54
154	DF	90	2.13	0.15	1.27
154	DF	100	1.52	0.00	1.27
154	GF	90	6.71	0.30	12.70
154	DF	70	5.79	2.44	12.70
154	GF	90	5.18	0.15	11.43
154	DF	90	2.44	0.15	1.27
154	PP	60	3.35	1.22	2.54
154	DF	80	1.83	0.30	1.27
154	DF	70	1.68	0.15	1.27
154	DF	60	1.52	0.30	1.27
154	PP	30	16.15	9.75	30.48
154	DF	30	11.58	3.35	22.86
154	DF	70	9.75	3.96	24.13
154	DF	80	11.13	1.52	24.13
154	DF	80	16.61	2.44	40.64
154	DF	90	8.23	0.91	20.32
154	DF	90	5.79	0.91	15.24
154	DF	90	10.36	1.37	21.59
154	DF	75	22.56	5.64	49.53
154	GF	90	7.01	0.15	17.78
154	DF	80	9.30	1.83	24.13
154	DF	80	15.54	2.90	36.83
154	DF	90	10.21	1.52	25.40

154	DF	80	22.86	2.13	55.88
154	DF	70	23.77	4.27	74.93
154	DF	50	12.65	1.83	34.29
154	DF	50	17.37	6.71	30.48
154	DF	80	9.60	2.44	22.86
154	DF	70	13.56	3.20	19.05
154	DF	80	13.56	3.51	27.94
154	PP	30	19.66	10.06	34.29
154	DF	50	13.41	3.20	34.29
154	DF	40	11.43	8.69	27.94
154	DF	60	22.25	4.11	46.99
154	DF	70	12.50	1.98	27.94
154	PP	0	9.14	N/A	10.16
154	DF	75	9.91	0.15	21.59
154	PP	40	13.26	8.08	25.40
154	DF	70	11.43	2.74	26.67
154	DF	80	6.86	0.91	17.78
154	DF	30	11.13	4.27	21.59
154	DF	70	8.38	1.83	21.59
154	DF	40	12.19	3.96	26.67
154	DF	75	13.11	1.83	27.94
161	DF	70	18.29	1.52	45.72
161	DF	70	16.76	1.83	40.64
161	DF	90	9.75	0.61	22.86
161	DF	0	13.41	0.00	38.10
161	PP	30	16.76	4.88	35.56
161	DF	80	18.90	4.88	33.02
161	PP	85	3.51	0.30	13.97
161	PP	70	12.95	5.49	35.56
161	PP	80	3.81	0.15	13.97
161	GF	90	4.72	0.15	12.70
161	DF	80	17.83	0.46	40.64
161	DF	90	5.18	0.15	16.51
161	PP	25	5.49	0.15	20.32
161	DF	80	7.01	0.00	19.81
161	DF	80	5.79	0.00	22.86
161	DF	0	6.40	0.00	27.94
161	PP	30	7.16	0.30	31.75
161	DF	75	17.68	3.66	35.56
161	DF	80	16.76	5.03	43.18
161	DF	65	20.42	1.22	40.64
161	DF	50	23.77	5.49	43.18
161	DF	90	2.13	0.00	1.27

161	GF	90	1.83	0.00	1.27
161	GF	100	1.83	0.00	1.27
161	GF	100	1.98	0.00	1.27
161	PP	90	1.83	0.46	1.27
161	GF	70	1.83	0.15	1.27
161	GF	80	3.05	0.61	3.81
161	SW	80	3.96	0.00	3.81
162	GF	20	6.40	2.74	12.70
162	GF	30	3.20	2.44	11.43
162	GF	15	11.58	2.59	17.78
162	GF	30	26.97	7.16	34.29
162	GF	0	18.59	12.19	22.86
162	GF	0	24.54	13.26	19.05
162	GF	10	17.83	1.83	76.20
162	GF	70	6.71	3.81	12.70
162	GF	15	9.75	2.74	10.16
162	GF	5	6.40	5.49	2.54
162	GF	0	20.42	13.41	40.64
162	GF	80	13.72	2.44	25.40
162	GF	0	7.32	7.32	41.91
162	GF	70	2.44	0.91	2.54
162	GF	0	3.05	3.05	43.18
162	GF	0	2.44	2.44	35.56
162	GF	0	5.94	5.94	34.29
162	GF	10	1.52	0.91	1.27
162	GF	15	5.49	1.22	6.35
162	GF	20	12.80	2.44	17.78
162	GF	30	11.28	6.71	13.97
162	GF	40	27.74	7.62	38.10

APPENDIX B. Understory composition of all study sites.

Table X Understory vegetation distribution at each study site.

			Distribution		
Site #	Common Name	Scientific Name	1-30%	30-60%	60-100%
103	bear grass	*Xerophyllum tenax*	X		
103	bluebunch wheatgrass	*Pseudoroegneria spicata*		X	
103	corn lily	*Veratrum californicum*	X		
103	daisy asteracea	*Bellis perennis*	X		
103	honeysuckle	*Lonicera*	X		
103	lupine	*Lupinus*	X		
103	mullein	*Verbascum thapsus*	X		
103	PIPO seedlings	*Pinus ponderosa*	X		
103	thistle	*Cirsium vulgare*	X		
105	huckleberry	*Vaccinium parvifolium*		X	
105	pinegrass	*Poaceae*	X		
105	raceme pussytoes	*Antennaria racemosa*	X		
105	scouler willow	*Salix scouleriana*	X		
115	grand fir seedlings	*Abies grandis*	X		
115	maple leaf currant	*Ribes acerifolium*	X		
115	vine maple	*Acer circinatum*		X	
119	bearberry	*Arctostaphylos uva-ursi*		X	
119	bear grass	*Xerophyllum tenax*		X	
119	lupine	*Lupinus*	X		
119	Oregon grape	*Mahonia aquifolium*	X		
119	pine grass	*Poaceae*			X
121	bearberry	*Arctostaphylos uva-ursi*	X		
121	bluebunch wheatgrass	*Pseudoroegneria spicata*			X
121	GF seedlings	*Abies grandis*	X		
121	huckleberry	*Vaccinium parvifolium*	X		
121	lupine	*Lupinus*	X		
121	pine grass	*Poaceae*			X
121	PIPO seedlings	*Pinus ponderosa*	X		
122	elk sedge	*Carex geyeri*	X		
122	Idaho fescue	*Festuca idahoensis*		X	
122	serviceberry	*Amelanchier*		X	
122	sitka alder	*Alnus incana*	X		
122	yarrow	*Achillea millefolium*	X		
124	beargrass	*Xerophyllum tenax*	X		
124	service berry	*Amelanchier*			X
124	yarrow	*Achillea millefolium*	X		
126	beargrass	*Xerophyllum tenax*	X		

126	cascade oregon grape	*Mahonia aquifolium*	X		
126	creeping snowberry	*Gaultheria hispidula*	X		
126	GF seedlings	*Abies grandis*	X		
126	serviceberry	*Amelanchier*	X		
128	bearberry	*Arctostaphylos uva-ursi*	X		
128	bear grass	*Xerophyllum tenax*			X
128	GF seedlings	*Abies grandis*	X		
128	oregon grape	*Mahonia aquifolium*	X		
128	pine grass	*Poaceae*	X		
128	PP seedlings	*Pinus ponderosa*	X		
128	service berry	*Amelanchier*	X		
128	sitka willow	*Salix sitchensis*	X		
129	bear grass	*Xerophyllum tenax*		X	
129	cascade oregon grape	*Mahonia aquifolium*	X		
129	pine grass	*Poaceae*		X	
129	service berry	*Amelanchier*	X		
129	yarrow	*Achillea millefolium*	X		
134	bear grass	*Xerophyllum tenax*		X	
134	few-flowered peavine	*Astragalus ceramicus*	X		
134	GF seedlings	*Abies grandis*	X		
134	meadow rue	*Thalictrum*	X		
134	service berry	*Amelanchier*	X		
134	shiny-leaf spirea	*Spiraea lucida*	X		
134	thimbleberry	*Rubus parviflorus*	X		
134	vine maple	*Acer circinatum*	X		
134	whitevein pyrola	*Pyrola picta*	X		
135	bearberry	*Arctostaphylos uva-ursi*		X	
135	bear grass	*Arctostaphylos uva-ursi*	X		
135	pine grass	*Poaceae*		X	
135	sitka alder	*Alnus incana*	X		
135	yarrow	*Achillea millefolium*	X		
138	bear grass	*Xerophyllum tenax*	X		
138	bracken fern	*Pteridium*	X		
138	cascade oregon grape	*Mahonia aquifolium*	X		
138	GF seedlings	*Abies grandis*	X		
138	pinemat manzanita	*Arctostaphylos nevadensis*	X		
138	shiny leaf spirea	*Spiraea lucida*	X		
138	spreading dogbane	*Apocynum androsaemifolium*	X		
153	pine grass	*Poaceae*			X
153	wild rye	*Elymus*			X
154	corn lily	*Veratrum californicum*	X		
154	lupines	*lupinus*	X		
154	oregon grape	*Mahonia aquifolium*	X		

154	pine grass	*Poaceae*	X	
154	PIPO seedlings	*Pinus ponderosa*	X	
154	yarrow	*Achillea millefolium*		X
161	corn lily	*Veratrum californicum*	X	
161	golden crown	*Coreopsis grandiflora*	X	
161	lupine	*Lupinus*	X	
161	pine grass	*Poaceae*		X
162	baldhip rose	*Rosa gymnocarpa*	X	
162	bear grass	*Xerophyllum tenax*	X	
162	bracken fern	*Pteridium*	X	
162	cascade oregon grape	*Mahonia aquifolium*	X	
162	pachistima	*Paxistima*	X	
162	sword fern	*Polystichum munitum*	X	
162	vanilla leaf	*Achlys*	X	
162	vine maple	*Acer circinatum*		X